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Design of a Clinical Boron Neutron Capture Therapy Treatment Facility: An Adaptation for University Honors Department senior project requirements

Joshua Taylor Carson
University of Tennessee - Knoxville

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Design of a Clinical Boron Neutron Capture Therapy Treatment Facility: an adaptation for University Honors Department senior project requirements

Joshua T. Carson
December 16, 1996

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Background

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The purpose of this paper is to adapt my nuclear engineering senior design project, "Design of a Clinical Boron Neutron Capture Therapy Treatment Facility," to the constraints and qualifications necessary to satisfy the requirements of a University Honors Program's senior project. In order to accomplish this goal, the remainder of this paper will focus on explaining the project in a non-technical fashion, the methods used by my group to complete the design project, my personal contributions to the design project, and my insights and opinions on the design project.

Design of a Clinical Boron Neutron Capture Therapy (BNCT) Treatment Facility - a project explanation

BNCT is an idea concerning the treatment and destruction of formerly inoperable tumors. Patients are given a solution of boron which is readily absorbed by and concentrated in the malignant tumor cells. Upon being exposed to a stream of neutrons, a boron atom will absorb a neutron and split into two particles. The separation, or fission, of the boron atom will generate enough energy to kill the malignant cell without harming the surrounding healthy cells. However, this process is far more difficult than it first appears. Not only must a neutron collide with a boron atom, that neutron must have a certain energy level when the collision occurs. If the energy level of the neutron is too high or too low, the desired separation of the boron atom will not occur.

As neutrons must not only engage boron atoms but engage them in a specific energy range, my design project focuses primarily on changing the energy of the neutrons when they arrive at the boron atoms, and secondly on designing a BNCT treatment center layout. As one possible source of neutrons for BNCT, Oak Ridge National Lab's Tower Shielding Reactor (TSR), lies within a short drive from Knoxville, my class's goal would be to design the treatment facility at the TSR and apply the above foci. The results and further

explanation of the project is contained in our final draft, "Design of a Clinical Boron Neutron Capture Therapy Treatment Facility."

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Selected from the students enrolled in the Spring 1996 section of Nuclear Engineering 472, my design group consisted of six students: Chet Ramsey, Cindy Maples, Don Marsh, Anne Robinson-Silber, Randy Hooker, and myself. Once we were assigned to groups, our first task was to decide how we wanted to approach this project. Following much discussion, we decided that we would begin our research by gaining an understanding of the history behind BNCT and the TSR. Once comfortable with the basic terminology associated with BNCT and the TSR, we began our second task, deciding upon the scope and organization of our work. Over the course of the next few weeks, we narrowed down the scope of our project to include the design of a shutter and collimator system for the TSR, as well as a design for the treatment facility. Eventually, we broke it down into fifteen basic elements, listed in section 1.4 of "Design of a Clinical Boron Neutron Capture Therapy Treatment Facility." We then assigned group members to work in various categories according to his/her interests and skills. Around this time in the project we decided that in order to promote efficiency among the group that we would need to appoint group leader. Although the group leader would be expected to assist and to assign work to other team members, he/she would also have to perform duties of his/her own, which weighed heavily upon our decision when electing a member to this position. Eventually, Chet Ramsey was appointed our group leader. After breaking down the project and assigning group members to specific tasks, the final, and most difficult aspect, of our project was to accumulate all of the information we had collected and insert it into a report fashion. This proved to be troublesome as combining the thoughts and ideas of six unique individuals is a combination of much time and patience.

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In addition to performing some common tasks of the group (e.g., background research, report editing, and report writing), I concentrated my efforts primarily on the economic, licensing, and mechanical design

aspects of our design project. Obtaining estimates on the construction of the BNCT facility, discussing and determining necessary equipment and personnel for the facility, collecting estimates on the equipment and personnel, determining approximate cost of treatment, estimating start-up, maintenance, operating, and decommissioning costs, and determining the cost of licensing the facility were primary interests in the economic analysis of our design. In order to accomplish these tasks, I had to contact multiple individuals who were knowledgeable on many different subjects. For instance, to obtain an estimate for the construction of our proposed facility, I discussed the floor plans with Randy and Cindy to determine the absolute necessary components for construction (e.g., the treatment room must have concrete walls) and then spoke with different contractors who would be able to bid on such a job. In order to determine what equipment and personnel would be necessary to operate such a facility, I spoke with several chemists, doctors, and nurses who provided valuable opinions. After deciding what we needed, I then had to contact distributors of the equipment to obtain estimates. Much of my time was also spent discussing the estimated start-up, maintenance, shutdown, and decommissioning costs with several individuals at Tennessee Center for Research and Development, a Knoxville company currently working on a feasibility study for a BNCT treatment facility at the TSR.

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Design of a Clinical Boron Neutron Capture Therapy Treatment Facility

Chet Ramsey
Cindy Maples
Don Marsh
Anne Robinson-Silber
Josh Carson
Randy Hooker

Undergraduate Entry
University of Tennessee, Knoxville

April 17, 1996

American Nuclear Society
Student Design Competition

Faculty Advisor
Dr. H. L. Dodds, Jr.

Nuclear Engineering Department
The University of Tennessee, Knoxville

Dedication

We would like to dedicate our work to the 5415 people that die every year from Glioblasoma Multiform

Acknowledgments

We would like to thank the following individuals for their time and expertise in speaking to our design class: G. Flanagan, D. Ingersoll, C. Slater, and W. Hill of Oak Ridge National Laboratories, G. Dilworth and C. Wilson of the Tennessee Center for Research and Development, G. Kabalka of the University of Tennessee Chemistry Department and R. A. Lillie. We would also like to thank R. Pevey and S. Goluoglu for their tireless efforts and assistance with DORT and other computer codes. An additional thanks to C. Wilson for his input in the economic analysis and to G. Kabalka for assistance in the medical facility design. Our thanks to T. Kerlin for reviewing our original report draft. Finally to H. L. Dodds, our sincere gratitude for his efforts in coordination and organization of our project.

Abstract

The goal of this design project is to develop a conceptual design of a clinical facility for Boron Neutron Capture Therapy that utilizes Oak Ridge National Laboratory's Tower Shielding Reactor as the neutron source. The primary focus of this report is to develop an overall facility design as well as designs for a conceptual beam collimator and beam shutter. Additionally, system safety and facility economics are addressed.

The overall facility design includes treatment rooms, a confinement building, and supporting medical facilities. The medical facilities support the outpatient treatment of cancer patients in a comfortable environment. The treatment room and confinement building provide protection for the patients, environment, and personnel during normal and abnormal operations. Facility economics are evaluated for startup, maintenance, operating, and decommissioning costs as well as income generated from treating patients.

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Chapter 1

Introduction

1.1 Background

In the United States 1,515 people die every day from all types of cancer.[22] At present, the only way to survive is with an effective treatment, but with some forms of cancer there is none. An ideal treatment for cancer would ignore normal cells while simultaneously seeking out and destroying rapidly dividing cells.[3] With today's medical, chemical, and nuclear technology, a procedure based on these principles has been successfully administered.

Boron neutron capture therapy (BNCT) is a treatment that brings together two components that individually have little effect on normal tissue. The first component is a chemical compound that contains the stable isotope boron-10, and the second is a beam of neutrons. When injected into the body, the chemical compound will concentrate in cancerous cells. After a short period of time, the boron compound is biologically removed from normal tissue. When the boron-10 absorbs neutrons it subsequently decays by alpha emission. The alpha particle and the recoiling lithium atom deposit most of their energy inside the cell containing the original boron.[2] The result of this reaction is a deadly radiation field of heavy particles localized to tumor cells as shown in Figure 1.1.[17]

Although treatment such as surgery, chemotherapy, and radiation have successfully treated many types of cancer, there are some forms for which BNCT is the only solution. One of the most highly malignant and resistant of all cancers is Glioblasoma Multiform (GBM). GBM is a cancer of the glial supportive tissue of the central nervous system (CNS). Glial cells, which make up over 90 percent of the CNS, provide chemical and physical support to neurons. Unlike neurons, glial cells are extremely susceptible to cancer because they are constantly undergoing mitosis. The standard treatment for GBM is an external beam of 4 to 6 MeV X-rays, given in doses of approximately 60 Gy administered in fractions of 1.8 to 2.0 Gy daily five days a week.[31] Unfortunately, this method destroys much of the intervening healthy brain tissue in the beam path, and unless every cancer cell is killed, there is a possibility that the cancer will reestablish itself. The median survival rate for treated GBM ranges from eight to fourteen months while untreated GBM results in a median survival rate of three months.

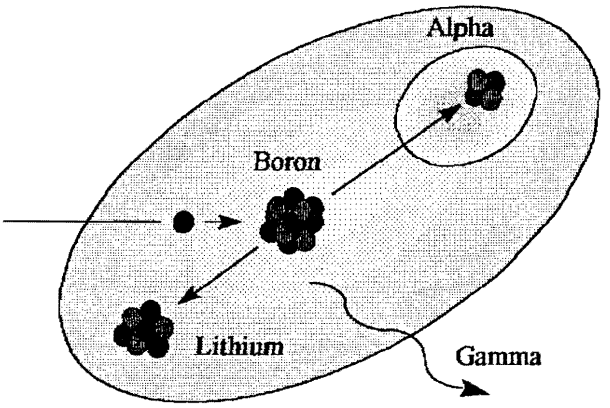


Figure 1. 1 Schematic of the Boron-10 Neutron Interaction

During 1995, approximately 323,000 people in the United States died from brain, colon, skin, lung, breast, and prostrate cancer, all of which could have been treated with BNCT. If proven effective, over 90,000 patients yr^{-1} could qualify for BNCT. The life extension and higher quality of life beyond conventional treatments could potentially return over $73 billion to the U.S. Treasury over a 10 year period.[14]

1.2 Design Objectives

The goal of this design project is to develop a conceptual design of a clinical facility for Boron Neutron Capture Therapy that utilizes Oak Ridge National Laboratory's (ORNL) Tower Shielding Reactor (TSR) as the neutron source. The primary focus of this project is to develop an overall facility design as well as designs for a conceptual beam collimator and beam shutter. Additionally, system safety and facility economics will be addressed by the final design.

The beam collimator should be designed in order to maximize the dose delivered to the tumor and minimize the dose delivered to the rest of the body by varying the diameter, thickness, material, and angle of the collimator as shown in Figure1.2. The neutron

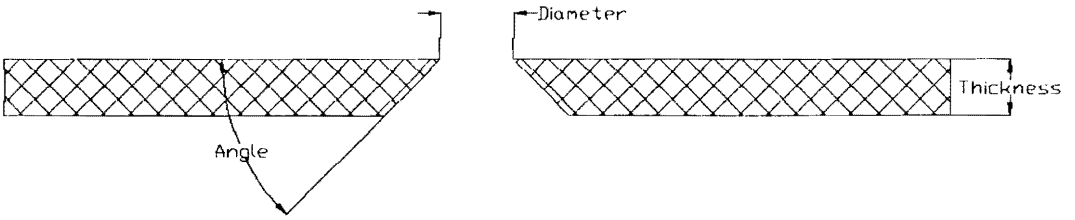


Figure 1.2 Collimator Design Parameters

fluence incident on the collimator is anisotropic and equally distributed across its surface. In order to minimize radiation exposure to the body, the neutron leakage from the reactor is collimated into a narrow beam.

In order to maximize the number of patients treated daily and reduce stress on the reactor core, the reactor will not shut down between treatments. A shutter should be designed to reduce the radiation exposure in the treatment room to levels as low as

reasonably achievable, thus allowing unrestricted entry for attending personnel. The shutter design should also contain a safety system to insure closure during both normal and credible abnormal operations.

The overall facility design includes treatment rooms, a confinement building, and supporting medical facilities. The medical facilities will support the outpatient treatment of cancer patients in a comfortable environment. The treatment room and confinement building will provide protection for the patients, environment, and personnel during normal and abnormal operations. Facility economics will also be evaluated for startup, maintenance, operating, and decommissioning costs as well as income generated from treating patients.

1.3 Scope and Organization of Work

Chapter 2 of this report summarizes the history and previous research that has gone into making boron neutron capture therapy a viable treatment method. This section also summarizes the work that has gone into boron chemistry, animal testing, and clinical trials.

Chapter 3 describes the selection process for finding an appropriate neutron source. The advantages and disadvantages of different types of neutron sources are discussed. The final selection of the Tower Shielding Reactor is also discussed.

Chapter 4 summarizes the design of the hydraulics used to move the shutter. Safety systems and interchangeable filters are also discussed.

Chapter 5 summarizes the design of the shutter for the neutron beam. This section discusses the materials chosen for the shield.

Chapter 6 summarizes the design of the collimator for the epithermal beam. This section also discusses the materials and geometry chosen for the fabrication of the collimator.

Chapter 7 summarizes the design of the facility including the medical, chemical, and nuclear aspects. Related equipment required for standard operations and safety are also discussed. Additionally, suppliers and cost estimates for the overall facility and related equipment are also given in Chapter 7.

The complete facility design is provided in Chapter 8. A total cost estimate for the start-up, maintenance, operating, and decommissioning is discussed. Treatment cost and revenue generated are also discussed in Chapter 8.

Chapter 9 describes work that needs to be considered for the future.

1.4 Work Breakdown Structure

	Joshua Carson	Randall Hooker	Cynthia Maples	Donald Marsh	Chester Ramsey	Anne Robinson-Silber
Background Research	X	X	X	X	X	X
Collimator Design Cases				X	X	X
Economic Analysis	X				X	
Economic Research	X	X	X	X	X	X
Equipment Research		X	X	X	X	X
Facility Design		X	X			
Facility Research	X	X	X	X	X	X
Familiarization with Codes			X	X	X	X
Licensing Research	X		X			X
Materials Research				X	X	X
Mechanical Design	X		X	X	X	X
Medical Research		X	X		X	
Report Editing	X	X	X	X	X	X

Report Writing	X	X	X	X	X	X
Shutter Design Cases				X	X	X

Chapter 2

BNCT History

2.1 Initial Clinical Trials[15]

The therapeutic potential of boron neutron capture therapy is not a new idea. It was a dream first conceptualized in 1936 by G.L. Locher of the Franklin Institute, but was not given form until 1951 by W.H. Sweet. Sweet and his colleagues first demonstrated that the chemical compound borax would concentrate in tumor cells in the human brain. Shortly thereafter, clinical trials were initiated at the Brookhaven National Laboratory (BNL) in conjunction with the Massachusetts General Hospital. The trials at BNL were carried out from 1951 to 1952 and additional trials were carried out from 1961 to 1962 at the Massachusetts Institute of Technology (MIT). Unfortunately, the trials failed to show any therapeutic advantage, and in some cases, actually shortened the patient's life. The first boron compounds used did not achieve selective localization in the tumor due to their diffusibility and low molecular weight. This, combined with a beam of thermal neutrons that was rapidly attenuated in tissue, resulted in massive damage to adjacent skin and brain.

Fortunately, one of the researchers, H. Hatanaka, returned to Japan to continue working on boron neutron capture therapy. Dr. Hatanaka treated over a hundred patients with a wide variety of tumor grades and history with promising results, as shown in Figure 2.1. Group 1 represents 46 patients who received chemotherapy and radiation treatment

before their BNCT treatment. Group 2 represents all 38 patients that received only BNCT between 1968 and 1985. Group 3 represents the twelve BNCT patients with tumors less than six centimeters from the surface of the brain. Group 4 represents the eleven patients treated between 1987 and 1989. The five year survival rate for Group 3 patients was 58.3 percent and 68 percent for Group 4. The five year survival rate with conventional surgery, chemotherapy, and radiotherapy was 4.6 percent.

2.2 Boron Chemistry[23]

Several nuclides have high cross sections for thermal neutrons, but boron-10 is the only one that is ideally suited for BNCT. Boron-10 is not radioactive and is readily

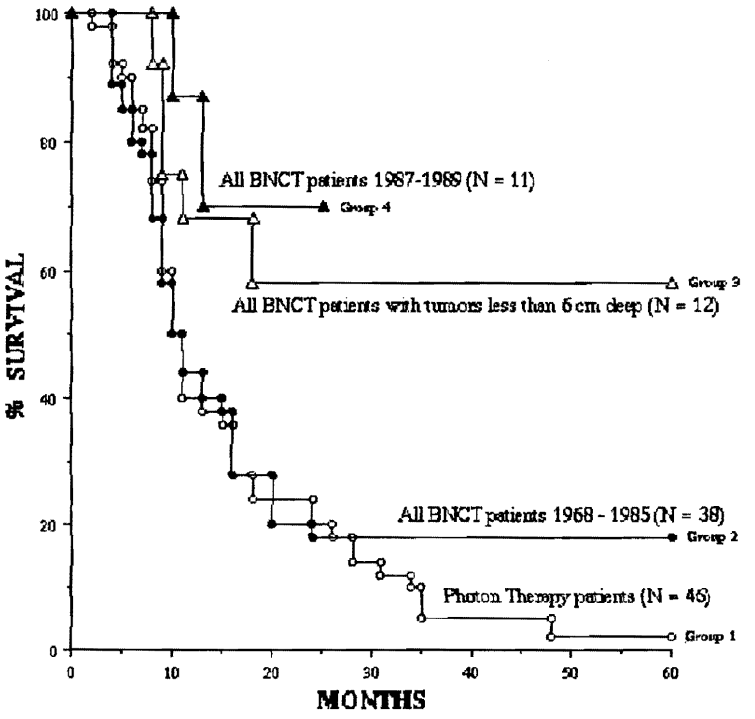


Figure 2. 1 Hatanaka Data

available, comprising approximately 20 percent of naturally occurring boron. The particles

emitted by the neutron capture reaction $^{10}B(n,\alpha)^{7}Li$ have a high Linear Energy Transfer (LET), and their path lengths are approximately one cell diameter (10 microns). This effect theoretically limits the radiation damage to tumor cells that have taken up a sufficient amount of boron-10. Another advantage of boron-10 is that the alpha particles can kill dividing and non dividing cells alike. This is important because tumors are known to have a large number of viable but inactive cells, and other forms of radiation treatment and chemotherapy work best only on cells that are dividing.

Boron compounds used in BNCT have a high specificity for malignant cells with low concentrations in normal tissue and blood.[10] Initially, boron compounds such as sodium borate and boric acid were selected for their availability, known pharmacology, and lack of toxicity. The differences in the concentration between the tumor and brain for these chemicals, which was small to begin with, dissipated over a period of 1 to 2 hours. These shortcomings prompted a major effort in boron chemistry, which resulted in over a hundred compounds being screened.[6] Eventually, p-carboxybenzeneboronic acid and sodium decahydrodecaborate were selected for the first clinical trials at MIT.

Researchers at Shionogi Research Laboratories developed and synthesized the compound $Na_2B_{12}H_{11}SH$, also known as BSH, for use in BNCT.[18] Dr. Hatanaka determined boron uptake by surgically collecting tissue samples from 57 patients. These patients received BSH doses of 30 to 80 mg per kilogram of body weight approximately twelve hours before neutron irradiation. The average concentration was 26.3 ppm in the tumor and 18.2 ppm in the blood, and the mean tumor to blood ratio was 1.69.

Recently, there has been an increasing interest in the boron containing amino acid boronophenylalanine (BPA).[11] In Japan, BPA was used as a capture agent for BNCT of melanomas in both humans and animals.[24] BPA has a very low toxicity, a high affinity to tumor calls, a tumor-to-blood ratio of 3.5, and a tumor-to-brain ratio of 3.9.[28] It is these characteristics that make clinical BNCT possible.[4]

2.3 Current Clinical Trials[25]

Dr. Hatanaka's patients are treated with a thermal neutron beam that has a penetration of 3 to 4 centimeters. In order to treat deep seated tumors, a craniotomy is performed to remove the scalp and skull. Even with the craniotomy the treatment lasts from 1 to 6 hours. To overcome this limitation, current BNCT research is directed at filtering out fast neutrons, thermal neutrons, and photons to produce an epithermal neutron beam with an energy range of 0.5 eV to 10 keV. An epithermal neutron beam passes through the skin and skull and moderates to thermal energy levels around 2 cm into the brain, allowing the treatment of tumors deeper than 4 cm without surgery. With an epithermal fluence of 1×10^9 n/cm^2 sec^{-1}, the treatment period is reduced to under one hour. [8]

At present, there are two groups in the United States using the epithermal neutron beam approach to treat patients on an experimental basis. In 1994 the Brookhaven Medical Research Reactor, as shown in Figure 2.2, received approval from the Food and Drug Administration (FDA) to treat 28 patients dying of GBM. In 1995 MIT began clinical BNCT trials, and the University of Missouri is conducting animal tests.[27] It is

expected that the FDA will give final approval for BNCT to be used as a clinical treatment within the next two years.[32]

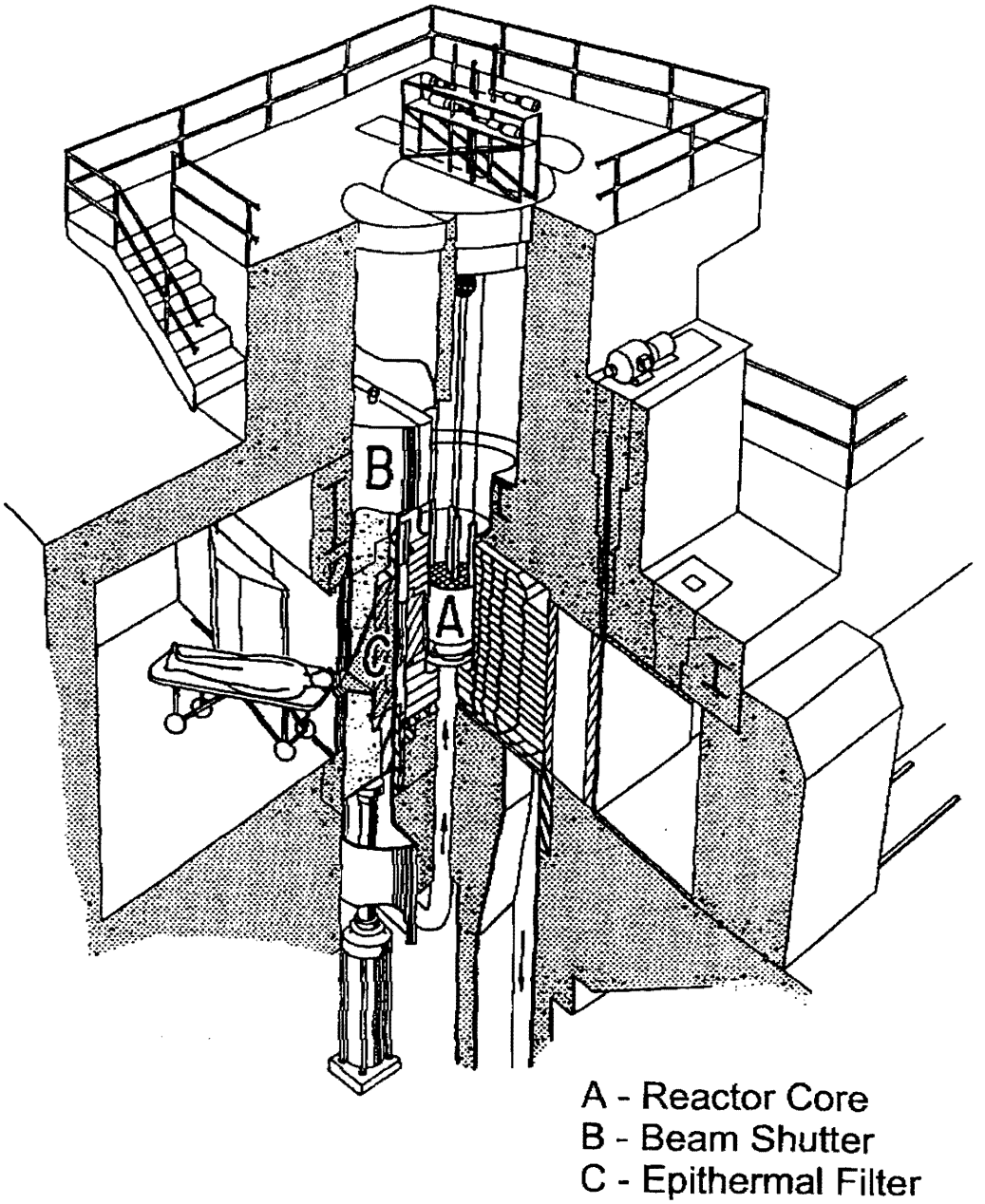


Figure 2.2 The Brookhaven Medical Research Reactor

Chapter 3

Site Selection

3.1 Neutron Sources

An epithermal neutron fluence rate greater than 1×10^9 neutrons cm^{-2} sec^{-1} is needed for successful boron neutron capture therapy. At the present time, only nuclear reactors are capable of generating such beams. There are approximately 35 research reactors, with power levels greater than 1 MW, in the United States that could potentially be modified for boron neutron capture therapy. The Brookhaven Medical Research Reactor, the MIT Research Reactor, and the Georgia Institute of Technology Research Reactor have irradiation facilities that were designed for medical and biological research.

One alternative source for the epithermal neutrons needed for boron neutron capture therapy is the spontaneously fissioning isotope californium-252. ^{252}Cf has a half-life of 2.645 years and decays by spontaneous fission 3.09 percent of the time. ^{252}Cf has a prompt neutron emission rate of 2.31×10^{12} (neutrons sec^{-1} g^{-1}). The entire supply of ^{252}Cf for the western world comes from the High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory, which produces less than a gram a year. Over a gram of ^{252}Cf is needed to produce an epithermal beam of neutrons of sufficient strength, thus making this option economically impossible. [39]

Epithermal neutrons for BNCT can also be produced in low energy proton accelerators. The main advantages of accelerator-based designs are a low mean neutron

energy from the source, low gamma ray contamination of the beam, low cost, ease of siting in or near hospitals, and a compact geometry. A neutron fluence rate of 1×10^9 neutrons cm^{-2} sec^{-1} can be obtained from a thick natural lithium target under bombardment by a 2.8 MeV proton beam operating at 10 mA. The high power density deposited in the lithium target by a such a beam would melt the lithium metal, even with the most efficient of forced water cooling systems. Although liquid lithium targets have been used experimentally, having liquid lithium and water in close proximity to the patient's head could present a serious problem should one of the cooling lines rupture. Until an advanced neutron target is developed, this method is not a feasible neutron source of BNCT.

3.2 Possible Reactor Sites in the United States[22]

Even if a nuclear reactor has a desirable neutron spectrum, it is usually not feasible for BNCT. Most reactors are contained inside pressure vessels surrounded by shielding. Some reactors are located in containment buildings or underwater in pools. In order to get an epithermal beam of 1×10^9 neutrons cm^{-2} sec^{-1} the patient must be located close to the reactor, because the fluence rate decreases by approximately r^{-2}. For most situations it is not possible to place a clinical facility inside a nuclear facility.

Extensive work has been done on the conceptual design of clinical facilities for BNCT at the Power Burst Facility (PBF) at the Idaho National Engineering Laboratory, the Missouri University Research Reactor (MURR), and the Georgia Institute of Technology Research Reactor (GTRR). Each of these facilities have outstanding neutron beam strength and purity, but each facility has its drawbacks. All three of these facility

share one common shortcoming: they are research facilities. The GIRR and MURR are university reactors that are primarily used for scientific research. If they are used for BNCT, other research projects will be conducted in the same area. Support facilities will be minimal and patients will be under external medical supervision. The PBF could function exclusively as a BNCT center, but at a price. In order to build a treatment room, a hot-cell needs to be decontaminated and a hole needs to be drilled in the reactor's pressure vessel.[13] The estimated cost for the conversion of the PBF is at least 30 million.

3.3 Possible Reactors Sites at ORNL[22]

Another possible location for a BNCT center is the Oak Ridge National Laboratory. ORNL has six potential epithermal neutron sources: the High Flux Isotope Reactor , the Oak Ridge Linear Accelerator, the Oak Ridge Research Reactor, the Bulk Shielding Reactor, the Health Physics Research Reactor, and the Tower Shielding Reactor. Unfortunately, only one of these reactors can be used for boron neutron capture therapy.

The High Flux Isotope Reactor is a versatile 100 MW reactor that has the highest thermal flux (2.5×10^{15} neutrons cm^{-2} sec^{-1}) in the world. The HFIR is used for medical and industrial isotope production, neutron scattering research, materials research, transplutonium isotope production, material irradiation, and neutron activation analyses. The HFIR currently has three tangential and one centerline beam tube from which to pull off neutrons. The best beam for BNCT would come from the centerline tube, but the flux

at the end of the epithermal filter, 1×10^{8} neutrons cm^{-2} sec^{-1}, would be an order of magnitude lower than what is required.

The Oak Ridge Linear Accelerator (ORELA) has a total neutron production rate of 0.8×10^{14} neutrons sec^{-1} at 50 kW. It has 18 flight stations positioned at 9, 20, 35, 40, 40, and 200 meters from the target. The flux at the closest target, 1×10^{7} neutrons cm^{-2} sec^{-1}, is two orders of magnitude lower than what is needed for BNCT. [1,21]

The Oak Ridge Research Reactor (ORR), the Bulk Shielding Reactor (BSR), and the Health Physics Research Reactor (HPRR) have all been shut down. The cost to restart one of these facilities and modify it for use in BNCT precludes there use.

The Tower Shielding Reactor, shown in Figure 3.1, can easily be restarted and modified for use in BNCT.[20] At present, the 1 MW Tower Shielding Reactor (TSR) is placed in a concrete shield on an unenclosed 30 meter long by 60 meter wide concrete pad. Because there is no building around the reactor, a nuclear and medical facility could easily be built on site around the existing structures. This one of a kind spherical core has a total neutron leakage of 1.2×10^{15} neutrons sec^{-1}. By adding a filter, an epithermal beam with a fluence rate of over 1×10^{9} neutrons cm^{-2} sec^{-1} is produced, allowing treatment times of less than 30 minutes. The reactor, location, and facility layout make it ideal for BNCT.

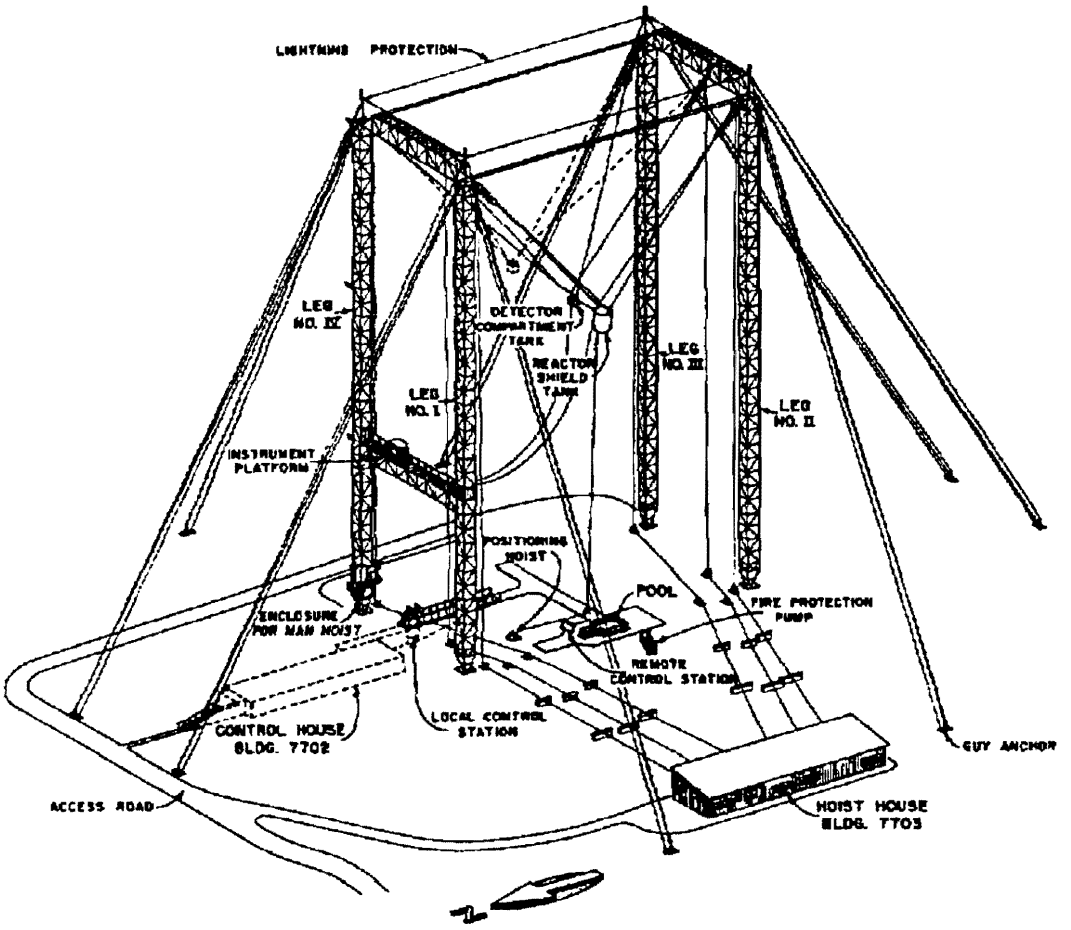


Figure 3.1 The Tower Shielding Facility

3.4 The Tower Shielding Facility[42]

The Tower Shielding Facility at ORNL was built in 1954 for shielding studies needed for the Aircraft Nuclear Propulsion Project (ANP). This research project required that the reactor radiation source be located in a region free from ground or structural scattering. After the ANP Project was canceled in the early 1960's, the facility was used to conduct a variety of experiments, including Space Nuclear Auxiliary Power, nuclear weapons shield studies, civil defense studies, the Liquid Metal Cooled Reactor (LMR)

program, the Gas Cooled Fast Reactor (GCFR) program, and for the conduction of large scale radiation transport studies.

The TSF consists of four 96 meter high towers erected on the corners of a 30 meter wide by 60 meter long rectangle. Two of the towers were originally used for suspending the reactor, while the other two were used for supporting other equipment such as shield components and detectors. In 1975, the reactor was placed in a ground-based concrete shield with a horizontal collimator, including a 80 cm diameter stepped cylindrical beam port. The shield and collimator were designed to allow placement of experimental mockups within 91 cm of the center of the reactor and to provide a relatively uniform spatial profile of the neutron source emerging from the beam collimator.

The reactor collimator opened onto a concrete pad 20 meters wide by 60 meters long. The radiation from fission and activation products in the core was attenuated by a large movable lead shutter. The shutter was opened only when all personnel were in an underground bunker which is covered with 107 cm of dirt and 46 cm of concrete.

The original Tower Shielding Reactor (TSR-I) was a boxed shaped 500 kW reactor. It was replaced in 1960 with the spherically symmetric TSR-II, which has been operated at power levels of up to 100 kW at both ground level and elevated positions. The TSF-II core consists of 60 mm thick curved aluminum-clad uranium-aluminum alloy plates cooled and moderated with light water. The plates are shaped so that the assembled core is a spherical fuel annulus from which radiation is emitted symmetrically. The neutron-absorbing control plates for the reactor are contained in the fuel-free region centered

inside the fuel annulus. Outside the fuel annulus is a reflector region that can be filled with aluminum-water, lead-boral-aluminum, or any other combination of material needed.

3.5 TSR Core Region[19]

The fuel annulus, the control ball, and the reflector are contained in the lower section of a cylindrical aluminum tank with a hemispherical bottom, as shown in Figure 3.2. This aluminum tank is 244 cm long , has an inside diameter of 94 cm at the hemispherical end, and an inside radius of 102 cm at the open end to allow maintenance procedures. The core consists of twenty-one fuel elements designed so that the fuel plates in adjacent elements join to form many concentric cylinders separated by water passages. The spherical annulus is 14 cm thick and has an outside diameter of 74 cm. Each fuel plate is 0.15 cm thick and consists of uranium-aluminum alloy clad in aluminum. The fuel plates are welded 0.30 cm apart into aluminum side plates to form fuel elements. Three types of elements are used: annular elements that form a cylindrical fuel annulus; central elements that are used in the upper and lower sections of the core; and one 7.62 cm diameter cylindrical plug element, which is centered in the lower central elements. There are 12 annular elements and 8 central elements in the reactor core.

The internal reflector region is filled by a 43.18 cm diameter sphere which contains six neutron absorbing control plates and the mechanism for positioning them to operate and shut down the reactor. The assembled control ball is mounted on four blocks which are welded on the inside of the central cylinder. Each control plate is a dished, hermetically-sealed hollow plate of 1.59 mm thick stainless steel filled with boron carbide.

Five shim safety plates move simultaneously relative to the fuel to operate the reactor. Each plate is independently driven toward the fuel, four outward and one downward, to shut down the reactor. The sixth regulating plate moves vertically in the upper region of the sphere and can be servo-operated to maintain the reactor power at a constant level. All cavities within the control ball are filled with water. Movement of the control plates is achieved by a combination of mechanical and hydraulic forces. As the control plates are pushed away from the fuel, a shutdown spring is loaded. In the case of an emergency shutdown, the shutdown spring will fully extend the control plates.

3.6 Core Heat Transfer [19]

The reactor was designed so that the surface temperature of the fuel plates is maintained below the saturation temperature of water at every point in the core. The saturation temperature in the core is 139.4 C at a pressure of 0.251 MPa. Under normal operating conditions, the cooling water flow rate is approximately three m^3 min^{-1} and the maximum allowable power is 1 MW. If the power level were raised to 3 MW and the cooling water flow rate was dropped to 1.5 m^3 min^{-1}, the maximum fuel temperature would be 96 C, which is below the boiling point even at atmospherics pressure.

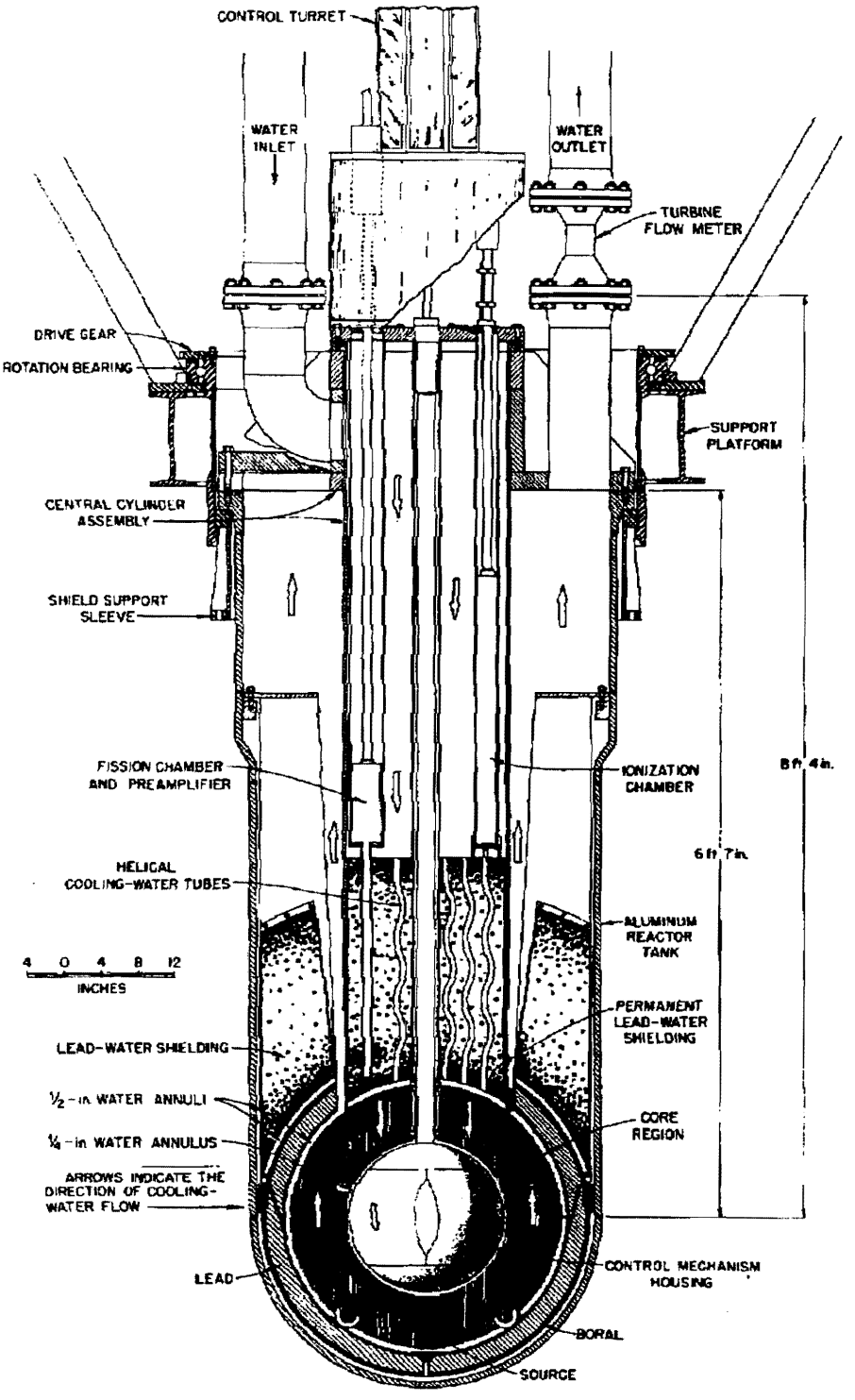


Figure 3.2 TSR Pressure Vessel

3.7 Site Location and Regional Support[42]

The Tower Shielding Facility is located approximately 9 miles from the city of Oak Ridge, Tennessee and 21 miles from the city of Knoxville, Tennessee. The site is located on the edge of ORNL and is easily accessible from Interstate-40. The TSF is easily accessible for the Southern, Northeastern, and Midwestern States.

Besides ORNL, a BNCT facility at the Tower Shielding Facility has enormous regional support. The Tennessee Center for Research and Development (TCRD) has shown an consistent interest in developing a clinical facility. Due to TCRD's efforts, the Department of Energy (DOE) has agreed to lease the TSF for up 99 years to interested parties.

The University of Tennessee, Knoxville can support all aspects of BNCT development and Treatment. Dr. George Kabalka from the Department of Chemistry is one of the countries leading authorities on boron chemistry and is currently active in the development of BPA and other advanced boron compounds. The University of Tennessee Medical Center and Cancer Clinic can provide medical therapies, radiological oncology, surgical procedures, pharmacological research, and patient diagnosis. The University of Tennessee also has one of two magnetic resonance imagining (MRI) machines in the country capable of imaging boron instead of hydrogen. Additional support can be provided by the Department of Veterinary Medicine for animal testing and by the Department of Nuclear Engineering for nuclear research.

Chapter 4

Beam Shutter Mechanism

In order to maximize the epithermal fluence rate to the patient during treatment, and minimize the total dose rate between treatments, a shutter mechanism is needed to turn the beam on and off. The shutter mechanism has passive safety features and the capability to interchange beam filters. The main limitations imposed on this design are the allowable dimensions, safety, availability of equipment, and cost of equipment.

4.1 Description of System and Operation

In previous experiments at the Tower Shielding Reactor the Large Concrete Beam Collimator (LCBC) acted as a horizontal shutter and collimator as shown in Figure 4.1.[42] Although the LCBC attenuates decay radiation from fission products and activated materials, it does very little when the beam is activated. By removing the LCBC, patients can be positioned 38.73 cm closer to the core of the reactor, producing a fluence rate increase of approximately 300 percent.

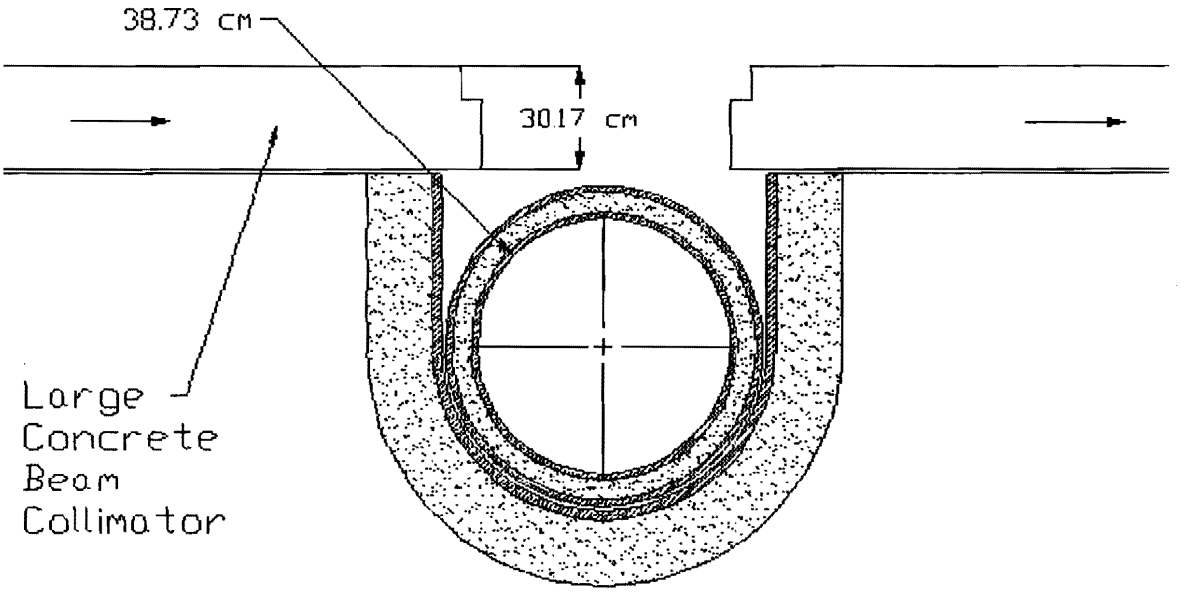


Figure 4.1 Existing Collimator/Shutter Configuration

In order to keep the patient as close to the reactor as possible, the shutter and filter should be attached and move together. Because the distance to the patient must be minimized, the shutter/filter assembly can only move horizontally or vertically, as shown in Figure 4.2. The horizontal configuration allows easy overhead access to both the shutter

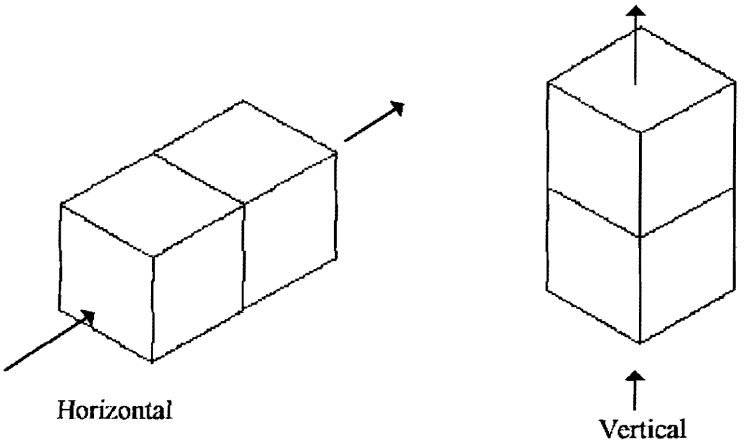


Figure 4. 2 Shutter/Collimator Movement

and the filter, but it is difficult to move. In the vertical configuration it is difficult to change the beam filter, but the system has gravity as an inherent safety feature.

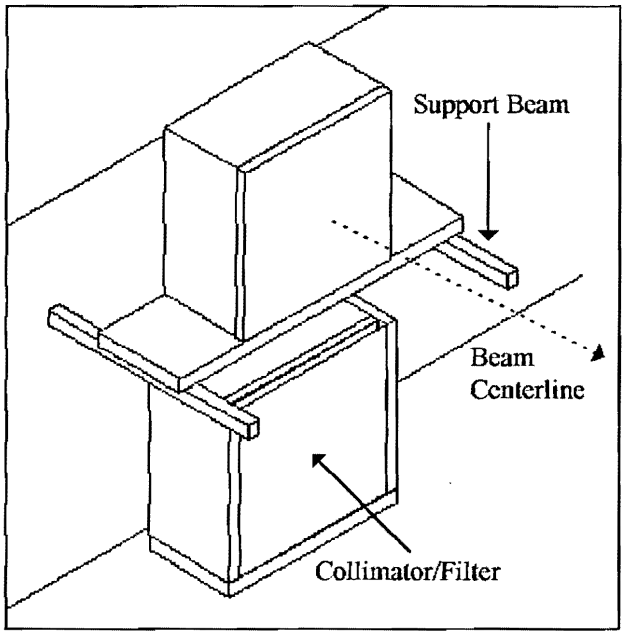


Figure 4.3 Shutter in the closed position

In order to get a fast, effective, and safe shutter/filter system, the best option is the vertical configuration hydraulically lifted with the shutter stacked atop the filter. The assembly would remain in the lowered position with the shutter in front of the reactor beam portal until the time for therapy to begin, as shown in Figure 4.3. At the beginning of the therapy the hydraulic system will activate and the filter and collimator will be lifted into the position between the reactor beam portal and the patient, as shown in Figure 4.4. At the end of the treatment session the hydraulics will lower and the shutter will again cover the beam portal, making the treatment room safe for facility workers to enter while the reactor is operating.

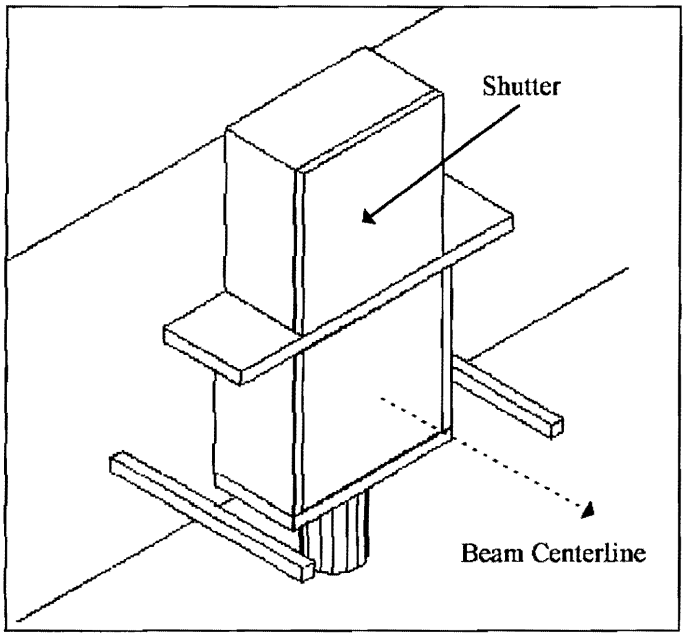


Figure4.4 Open shutter configuration

4.2 Interchangeable Filter Design

In order to maximize revenues, the BNCT Tower Shielding Facility can also treat melanoma, lung, colon, prostate, and breast cancer. Each type of cancer requires a unique filter and collimator, and this design has the capability to change the filter/collimator assembly with ease. A cross bar installed at the shutter rest position is capable of holding the shutter section of the assembly in place without the spectrum modifier in position. This allows the further lowering of the filter/collimator assembly clear of the cross bars. At this level the filter/collimator can be removed from either side and replaced with a different type of spectrum modifier and collimator.

4.3 Safety Features

The primary concern in this design choice is safety. This design employs an innate gravity safety feature; in the event of an accident where the hydraulics would fail, the assembly will fall into the closed position and end any radiation exposure to the patient. The shutter section of the assembly has been designed to be 50 cm wider than the spectrum modifier section of the assembly. Within this additional space there will be two dual purpose cross bars located at the base of the shutter when it is in the lowered position. These bars would provide a resting place and emergency support for the shutter should there be any reason that the spectrum modifier or hydraulics failed to support it. A series of guide bars are also placed along the side edges of the walls, beginning at the cross bar and extending to the top of the shutter in the raised position. These are to insure that the assembly does not move from its intended vertical course and that it cannot be inadvertently or accidentally removed from the beam portal opening. An additional hydraulic power unit, reservoir, and pump are included in the confinement building for system redundancy.

4.4 Hydraulic System Specifics[7]

The hydraulic lifting system for the filter/collimator assembly, shown in Figure 4.5, is required to raise approximately 11,000 kg 2.5 meters. For safety and future expandability of the facility, the lifted mass was rounded up to 18,000 kg. This height was determined from the maximum distance that the assembly will need to be raised plus an

additional amount for changing the filters. A vertical lifting force twice the weight of the

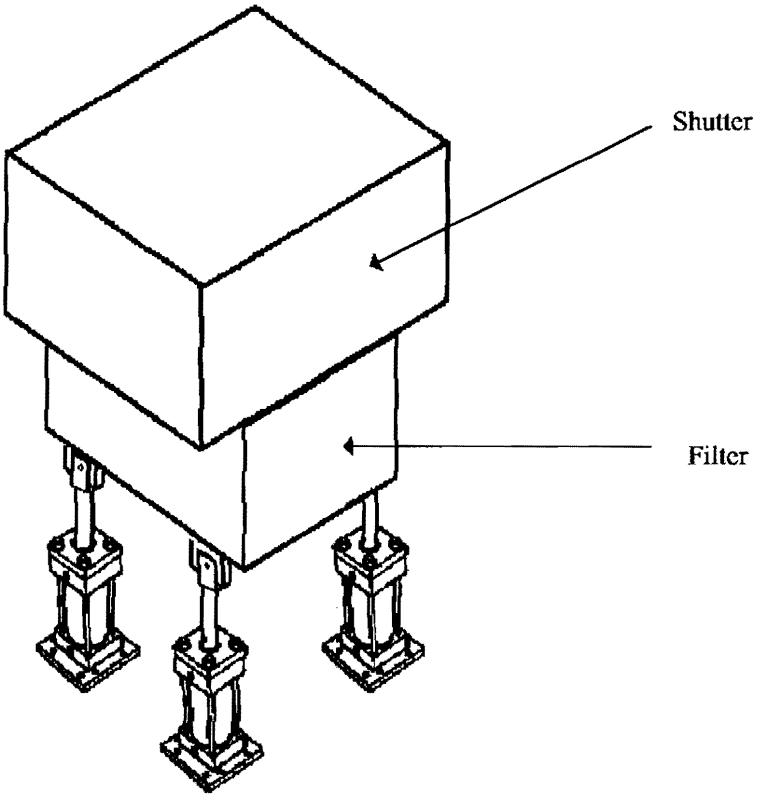


Figure 4.5 Hydraulic System

object being lifted is needed for fast operation. The hydraulic system required for this application consists of four separate five inch bore cylinders, each with a two inch diameter rod, capable of lifting over 37,000 kg. A cylinder is placed at each corner of a 110 cm wide by 72 cm long plenum on which the filter and shutter will rest. For added safety, an additional cylinder of identical dimensions is located at the center of the plenum so in the event that one of the exterior cylinders should fail, the assembly can be safely guided to the closed position. Each of the cylinders operate at 8.69 MPa delivering over 9,350 kg of force, which will more than adequately cover any future need of the facility. The cylinders can be obtained at an estimated cost of approximately $4,870 each. In

addition to the cylinders, a hydraulic power unit with a 114 liter reservoir and pump will be required. The estimated cost for the pump and reservoir is $3,500, and the miscellaneous tubing and fittings required to complete the system are an additional $750.

Chapter 5

Shutter Design

The beginning of the shutter assembly is located 53.66 cm from the center of the reactor. The combined neutron and gamma dose rate at this point is approximately 3×10^5 Sv hour^{-1}. The recommended annual limit for radiation workers is 50 mSv yr^{-1}.[38] In order to reduce the dose rate to acceptable levels, a shutter 110 cm thick must be constructed to attenuate the beam. The shutter must protect both the patient and the facility staff from unnecessary radiation exposures. The primary limitations imposed on the design are the allowable dimensions, mass, safety limits, cost, and feasibility of manufacture.

5.1 Shutter Calculations[44]

The shutter calculations were performed using XSDRNPM (X-Section Dynamics for Reactor Nucleonics with Petrie Modifications) running on a Sun SPARCserver 1000E with a 84 group P_5 cross-sections library and external source provided by ORNL. A program, called DOSE, was written to easily display the fluence and dose rates at the last spatial mesh point.[33]

5.2 Detailed Description of Shutter Design

In order to maximize the number of patients treated per day and to minimize operational stress on the reactor and control ball, the facility will operate at during treatment and 100 kW between treatments. A beam shutter is used to reduce the radiation levels in the treatment room to as low as reasonably achievable when the reactor is operated at 100 kW.

Approximately 84 different shielding models of varying thickness and composition were considered. Water and concrete are poor shields for this application, as shown in Table 5.1. The water shield thermalizes neutrons, but allows a large number of gamma rays to pass through uncollided. The concrete shield blocks the gamma rays, but allows the fast neutrons to pass through. A mixture of borated polyethylene and tungsten provide the best shield for the limited space. The borated polyethylene has a high hydrogen content, allowing it to thermalize the fast neutrons, while the tungsten provides gamma ray shielding.

Table 5.1 Shutter Calculations

Shielding Configuration	Dose (Sv/hr)
110cm Water	176
110cm High Density Concrete (HD)	6.64
80cm HD, 20cm Water, 1cm Cd, 9cm Pb	1.71E-02
10cm W, 72cm B-Poly, 18cm Bi, 10cm Li-Poly	8.16E-03
15cm Bi, 68cm B-Poly, 13cm W, 14cm B-Poly	3.68E-03
10cm W, 15cm B-Poly, 5cm W, 50cm B-Poly, 10cm W, 20cm B-Poly	1.70E-03

The final shutter design, shown in Figure 5.1, reduces the dose rate at 1 MW operating power to 1.70×10^{-3} Sv hr^{-1} on the wall closest to the reactor. When the reactor power is lowered to 100 kW, the dose rate drops to 1.07×10^{-5} Sv hr^{-1}, which is an acceptable limit with an occupancy factor of 4 hours per week

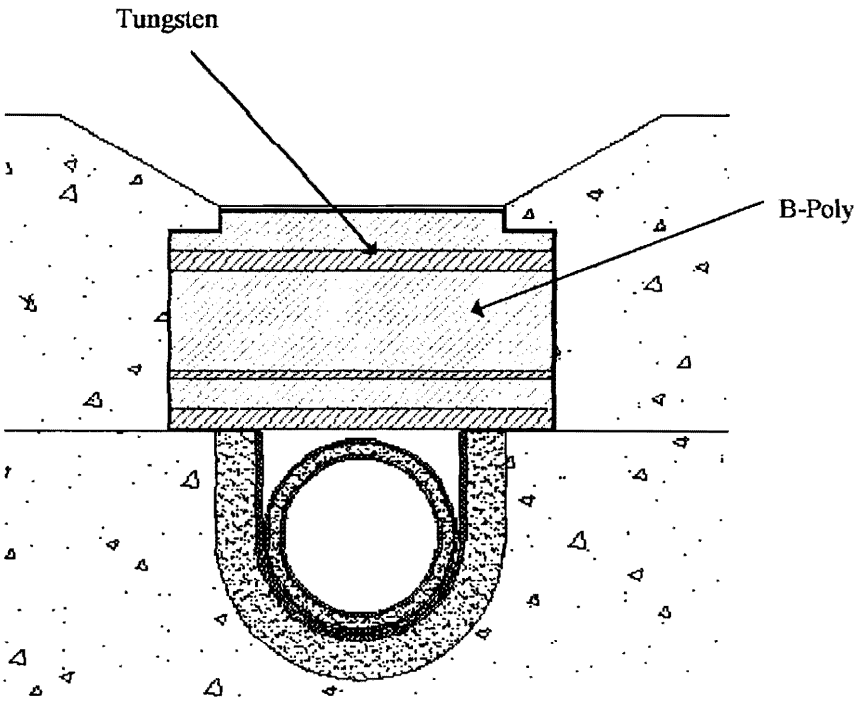


Figure 5.1 Final Shutter Design

Chapter 6

Collimator Design

The major criterion that one must consider when designing a collimator for use in boron neutron capture therapy is to deliver the highest possible thermal fluence to the brain, while administering the lowest achievable whole body dose. The spectrum of the beam is modified to the optimal spectrum for boron neutron capture therapy by a filter designed by engineers at ORNL. Other limitations imposed on the design the allowable dimensions, mass, safety limits, cost, and feasibility of manufacture.

6.1 Collimator Modeling and Calculations [43]

The two dimensional discrete ordinance program DORT is ideally suited for collimator and shielding design because it generates the exact fluence rate for each mesh point. An 84 group cross sections with P_5 scattering and a combined gamma ray and neutron source were provided by ORNL. All DORT calculations are performed on four Sun SPARCstation 20's, one SPARCserver 690, and one SPARCserver 1000E using P_5 scattering, a S-16 quadrature, 84 group cross sections, and the supplied reactor source. Although most calculations were finished in under an hour, DORT requires a large amount of disk space to store the output files and special programs to read them.

6.2 Programs to Analyze DORT Output[33,29]

Two programs were written to analyze the flux output from DORT. The first program, called FLIP (Flux Linear Interpolation Program), takes the boundary source provided by ORNL[26] and interpolates it to the intervals needed for the collimator geometry. This is necessary because ORNL's filter model has different intervals than what is needed for the design of the collimator. FLIP reads the intervals from an input file called READFLUX.INP, which contains ORNL's original intervals and the new collimator intervals.

The second program, called DRIP (DORT Reading Interpolation Program), reads the flux output from DORT. DRIP displays the fluence and dose rate for each energy group at points specified in an input file. The dose rate is calculated by multiplying the energy dependent 1991 ANSI standard dose response function, VELM61.DRF, by each energy group. The fluence and dose rates are displayed in a table and a Postscript flux map of the output is displayed.

A test was performed before running any calculations to verify that the source created with FLIP was the same as ORNL's. The fluence rate calculated with the modified source was compared to a sample problem supplied by ORNL at two points: 0,0 and 50,0. Both points were in close agreement, as shown in Figure 6.1 and 6.2.

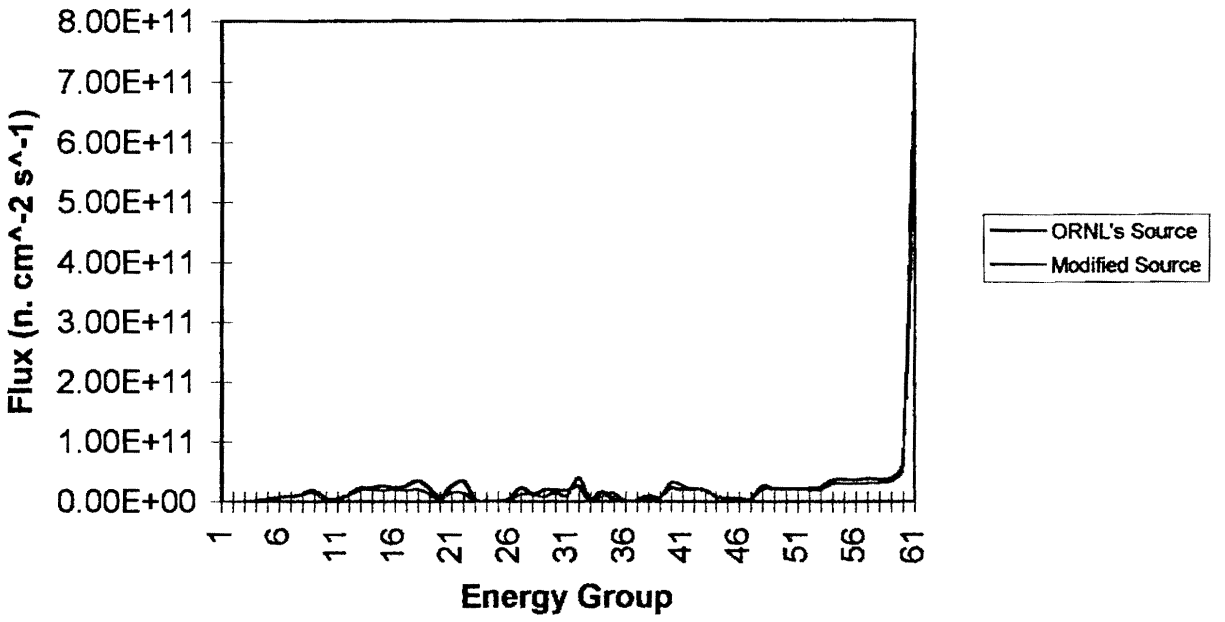


Figure 6.1 Verification of Source at Point (0,0)

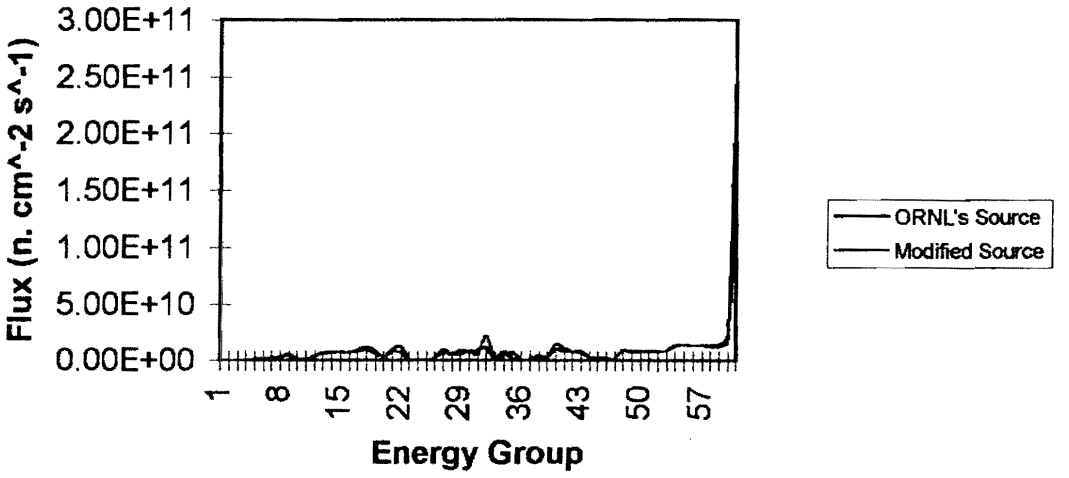


Figure 6.2 Verification of Source at Point (50, 0)

6.3 Collimator Optimization [41]

Three points of interest are used to determine the optimal collimator design. The first point is along the centerline of the reactor at the collimator exit where the epithermal neutron fluence should be the highest. The second point is 7 cm into the brain[9] where a high thermal fluence is needed. The third point is 50 cm to the right of the center of the brain where the total fluence rate should be low. This point is of importance because limiting the whole body dose is a major design restriction.

The first mesh used to model the filter and collimator consisted of approximately 13,000 one cm by one cm mesh points. In order to cut down the CPU time for each calculation, a course mesh of approximately 5,700 points was used instead of the fine mesh. A comparison of the fine mesh to the course mesh at the collimator exit is shown in Figure 6.3, and for 7 cm into the brain in Figure 6.4. Because the flux distributions are similar, the course mesh can be used to reduce runtime from 8 hours to under one hour.

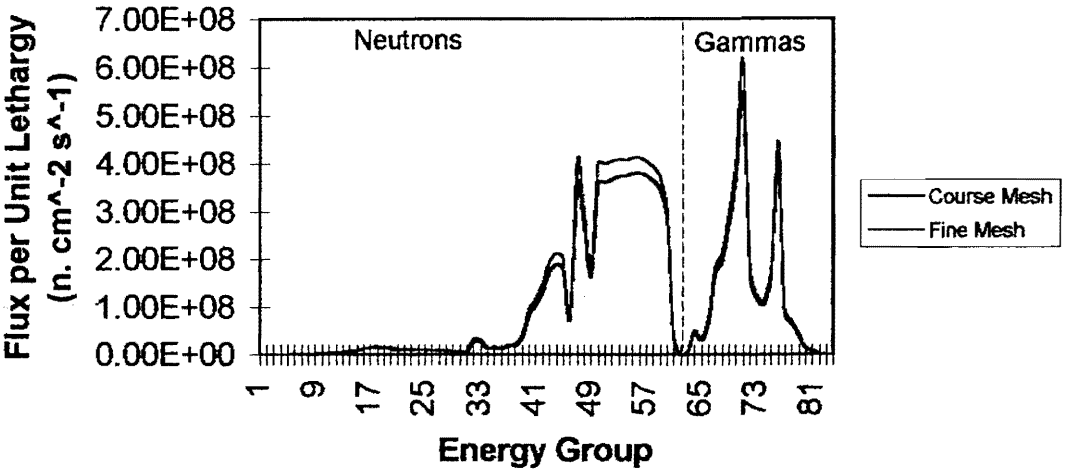


Figure 6.3 Comparison of Fine Mesh to Course Mesh at Collimator Exit

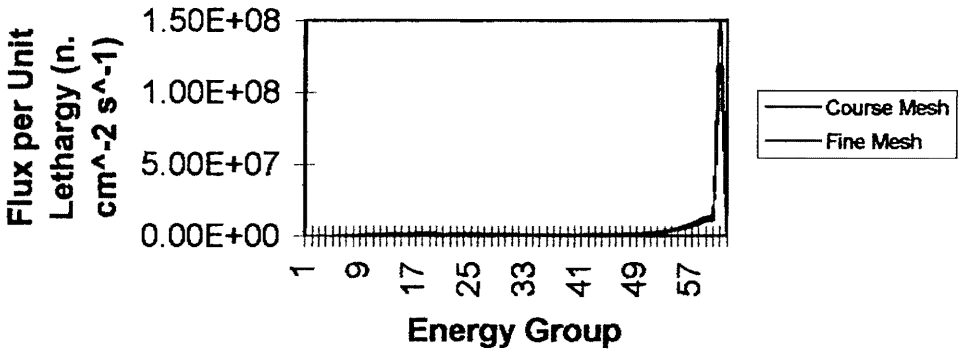


Figure 6.4 Comparison of Fine Mesh to Course Mesh 7 cm Into the Brain

In collimator design five properties are varied in order to achieve the optimal thermal neutron fluence and penetration into the brain. These properties include the collimator material, the radius of the opening, the angle of the collimator, the thickness of the collimator, and the overall position of the collimator, as shown in Figure 1.2 (page 3). Eighty-nine different collimator models were created and analyzed by varying these parameters.

Materials used in a collimator should rapidly moderate, absorb, and/or scatter neutrons so that the majority of neutrons reaching the patient are coming through the collimator opening. Lithiated polyethylene, lithiated paraffin, and borated polyethylene are good moderators because of their high hydrogen content. Lithium and boron have high absorption cross sections for thermal neutrons and decay by alpha emission. Out of five collimators made of lithiated polyethylene, lithiated paraffin, borated polyethylene, concrete, and aluminum, the lithiated polyethylene and aluminum collimators have the highest epithermal fluence rates. A comparison of the models at the collimator exit shows that the aluminum has a clear advantage over the lithiated polyethylene, as shown in Figure 6.5. A comparison of the two models seven cm into the brain shows that the aluminum has approximately two times the fluence rate of the lithiated polyethylene, as

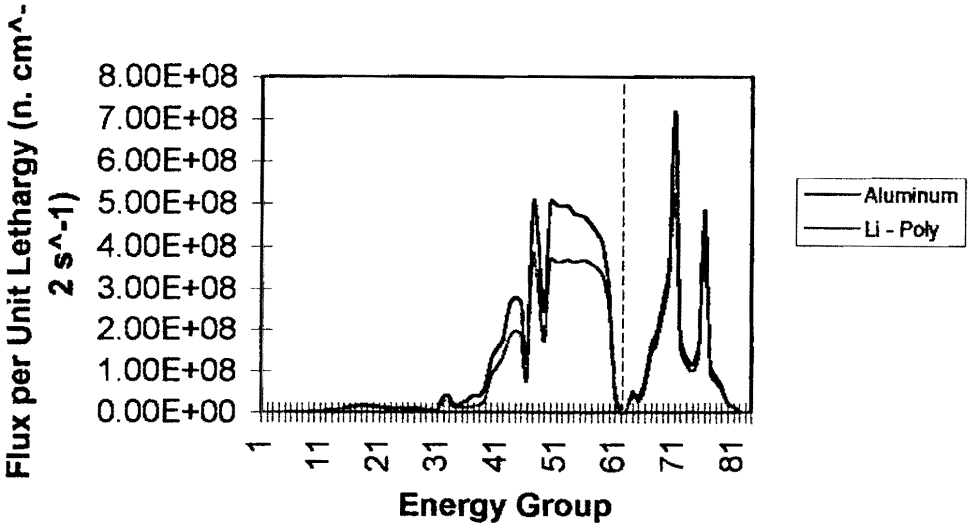


Figure 6.5 Material Changes at Collimator Exit

shown in Figure 6.6. Unfortunately, aluminum has a high epithermal and thermal fluence rate because it is a poor collimator. The neutrons that pass through the aluminum lose very little energy when compared to the lithiated polyethylene, as shown in Figure 6.7. In order to minimize the dose to the patient's body and maximize the epithermal fluence, lithiated polyethylene is used as the collimator material.

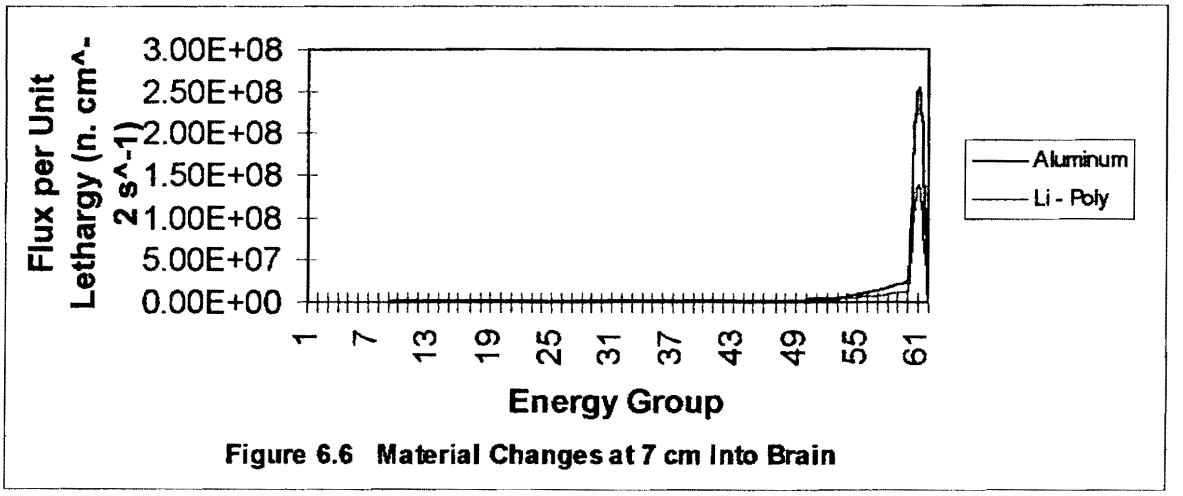


Figure 6.6 Material Changes at 7 cm Into Brain

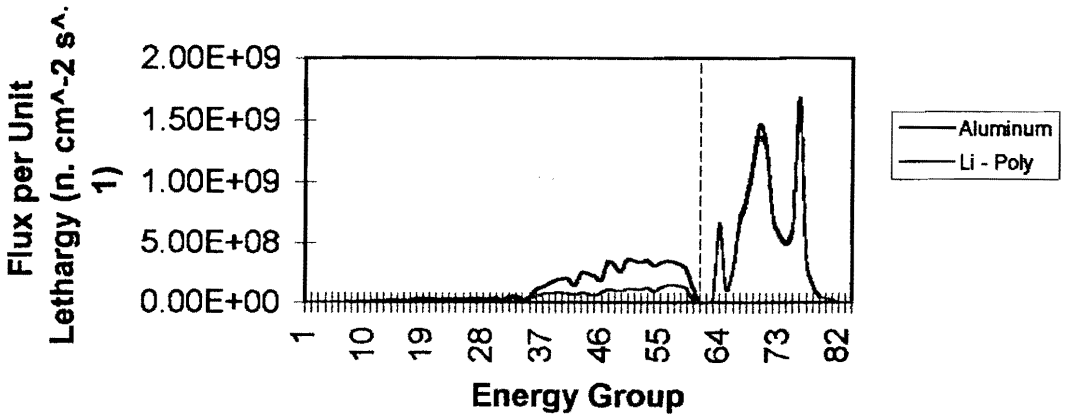


Figure 6.7 Material Changes at Collimator Exit

The radius of the collimator opening determines the size of the epithermal beam used during treatment. For the treatment of deep seated brain tumors, like GBM, a wide

collimated epithermal beam works better than a narrow collimated beam . Two models with a 6 cm and 9 cm radius are compared at the collimator exit in Figure 6.8. In order to maximize penetration, as shown in Figure 6.9 by the higher fluence rate, a 9 cm radius is used for the collimator opening.

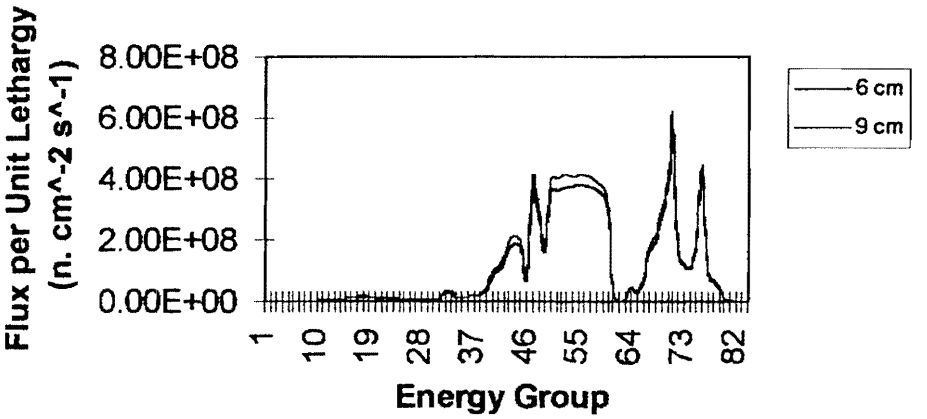


Figure 6.8 Radius Changes at Collimator Exit

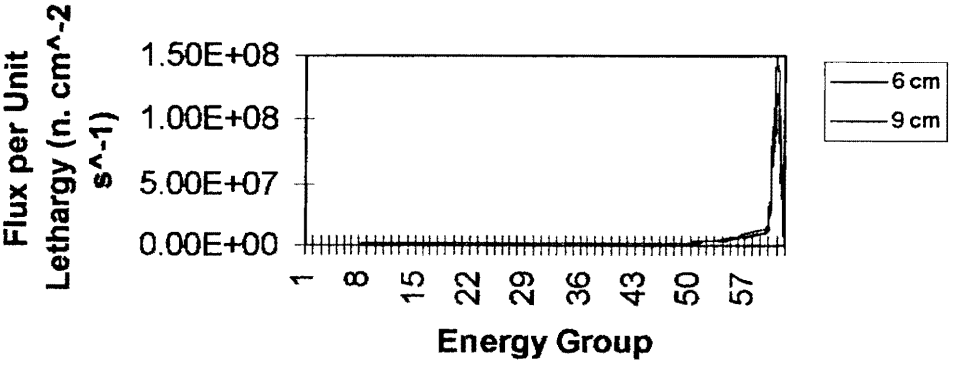


Figure 6.9 Radius Changes 7 cm Into Brain

By decreasing the angle of the collimator, the attenuation provided by the lithiated polyethylene is reduced. Although this allows more epithermal neutrons to pass uncollided, there is an associated increase in fast neutrons and gamma rays, as shown in Figure 6.10. The negative effects of the fast neutrons and gamma rays is outweighed by the positive effects from increased penetration provided by the eleven degree collimator, as shown in Figure 6.11.

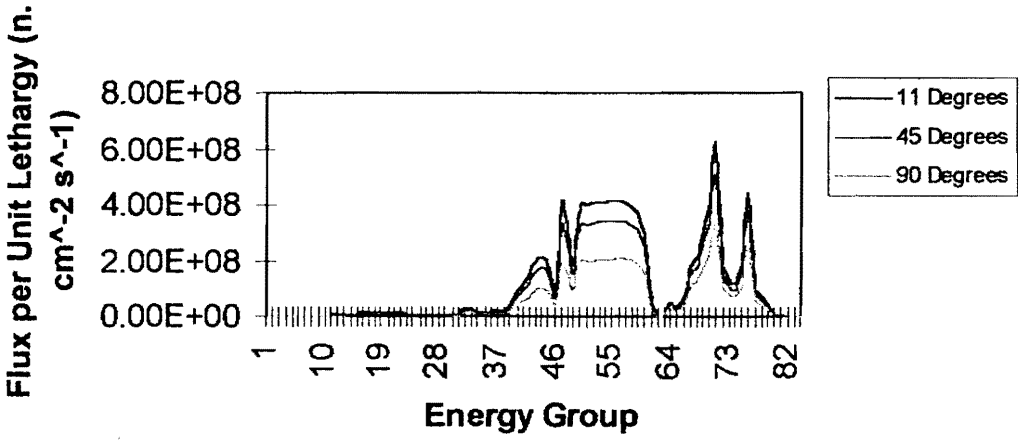


Figure 6.10 Changes in Angles at the Collimator Exit

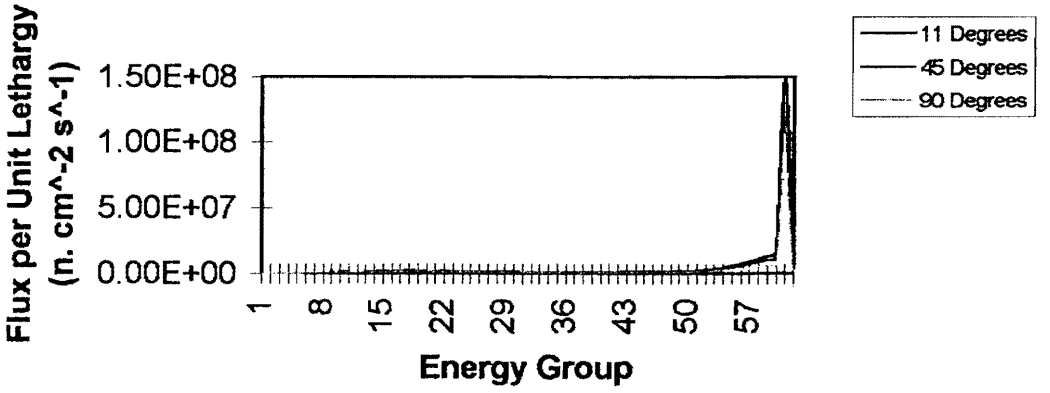


Figure 6.11 Angle Changes 7 cm Into Brain

Varying the thickness of the collimator has approximately the same effect as changing the collimator angle. By decreasing the thickness, more epithermal neutrons can pass through the collimator uncollided, as shown in Figure 6.12. Changing the thickness of the collimator does not drastically change the penetration. The real disadvantage of thin collimators is that they provide little protection to the patient's body, as shown in Figure 6.13. For this reason, a 10 cm thick collimator is used to reduce beam contaminates produced from lowering the collimator angle.

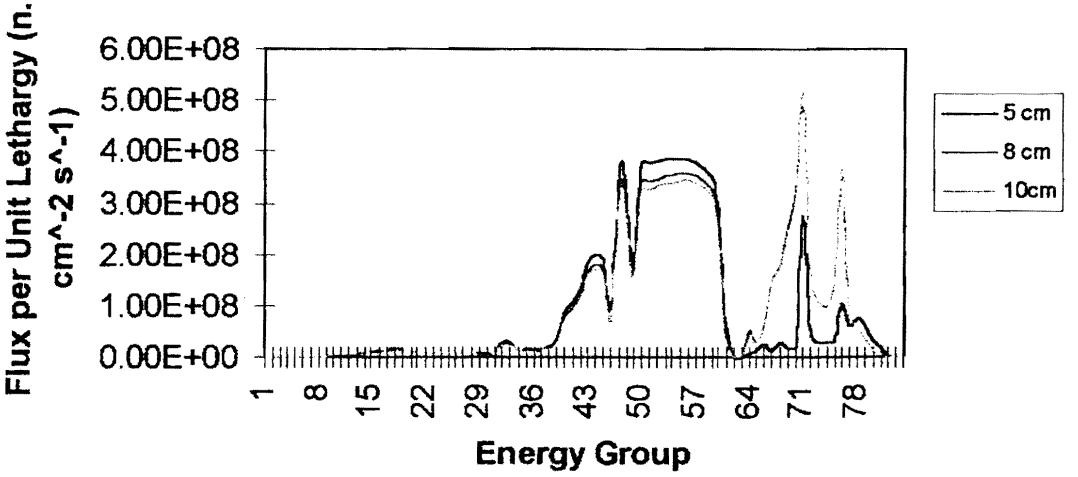


Figure 6.12 Thickness Changes at the Collimator Exit

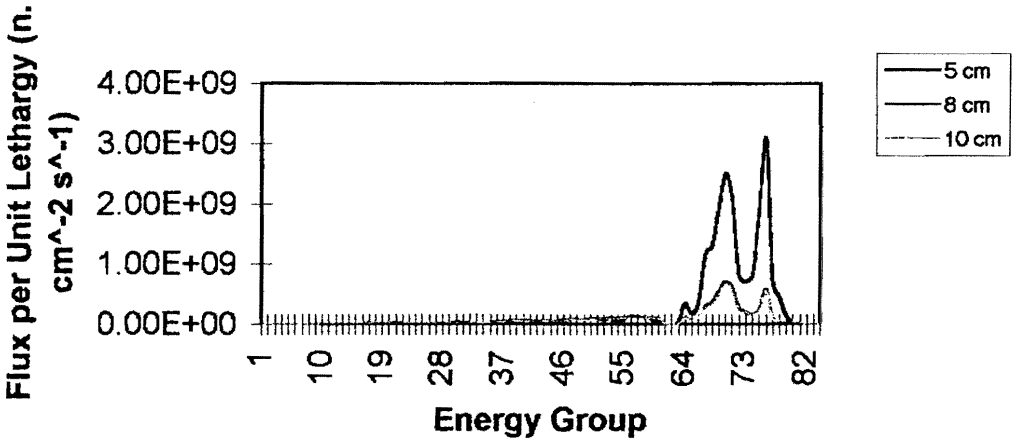


Figure 6.13 Thickness Changes 50 cm to the Right of the Brain

The overall positioning of the collimator with respect to the last layer of bismuth in the filter was examined. By placing the collimator inside the bismuth layer, the air gap is removed and the patient is moved closer to the reactor. A model with the collimator placed entirely in the bismuth layer with no air gap, a model with 5 cm of the collimator placed in the bismuth, and a model with the collimator in the normal position are compared. Even with the patient closer to the reactor, the standard collimator has a higher epithermal fluence rate at the collimator exit, as shown in Figure 6.14. Placing the collimator inside the bismuth not only lowers penetration but increases the gamma ray dose delivered to the patient's body, as shown in Figure 6.15. The geometry that optimizes the flux to the brain while minimizing the dose to the patient's body is the standard configuration.

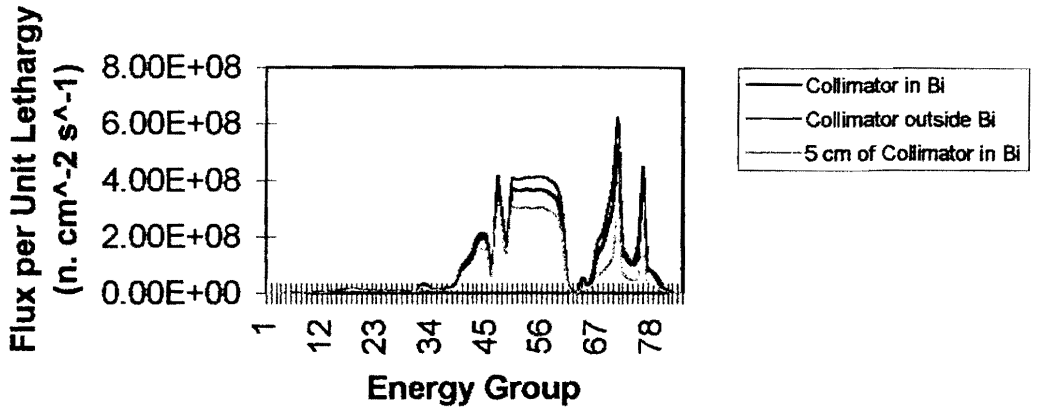


Figure 6.14 Position Changes at Collimator Exit

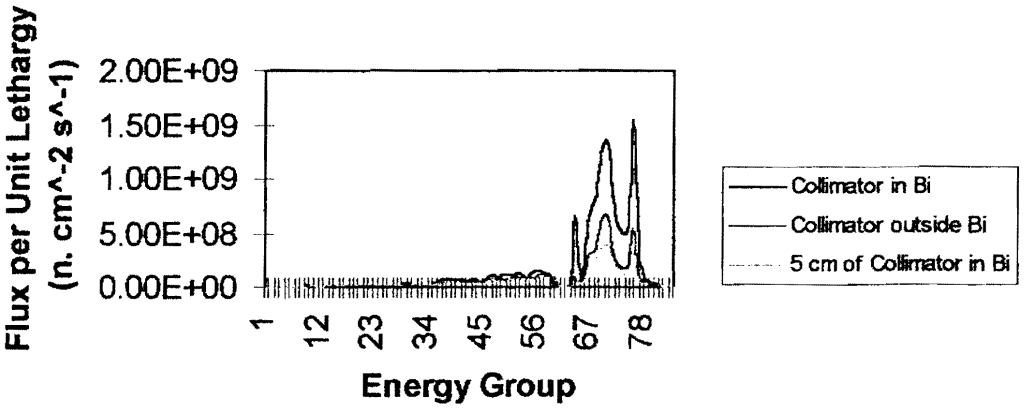


Figure 6.15 Position Changes 50cm to the Right of the Brain

6.4 Detailed Collimator Design

In order to decrease the amount of filter material used and increase the epithermal fluence rate at the collimator exit, the filter/collimator assembly is cylindrically shaped, wrapped in a reflector, and fits directly over the reactor beam port. Beryllium, lead,

tungsten, aluminum, and graphite were tested as reflectors. The test results are as shown in Table 6.1.

Table 6.1 Reflector Changes

Material	Epithermal Fluence Rate
Aluminum	3.44E+09
Lead	4.89E+09
Tungsten	3.04E+09
Graphite	1.32E+09
Beryllium	3.07E+09

In order to maximize the epithermal fluence rate, lead is used as the reflector even though it also increases the fast neutron fluence rate.

The final design is a 10 cm thick lithiated polyethylene collimator with a 9cm radius and an 11 degree angle. The collimator is attached to the filter and wrapped in lead as shown in Figure 6.16. The total neutron and gamma ray fluence rate across the outside surface of the final collimator is shown in Figure 6.17. The fluence rate decreases at an acceptable rate across the collimator, but some neutron leakage is still coming from the reflector and air gap. The thermal and epithermal neutron fluence from the exit of the collimator and through the phantom is shown in Figure 6.18. The thermal fluence rate peaks at approximately three centimeters into the brain, approximately five centimeters from the collimator, and then slowly decreases. With this thermal distribution, any tumor located in the head can be treated.

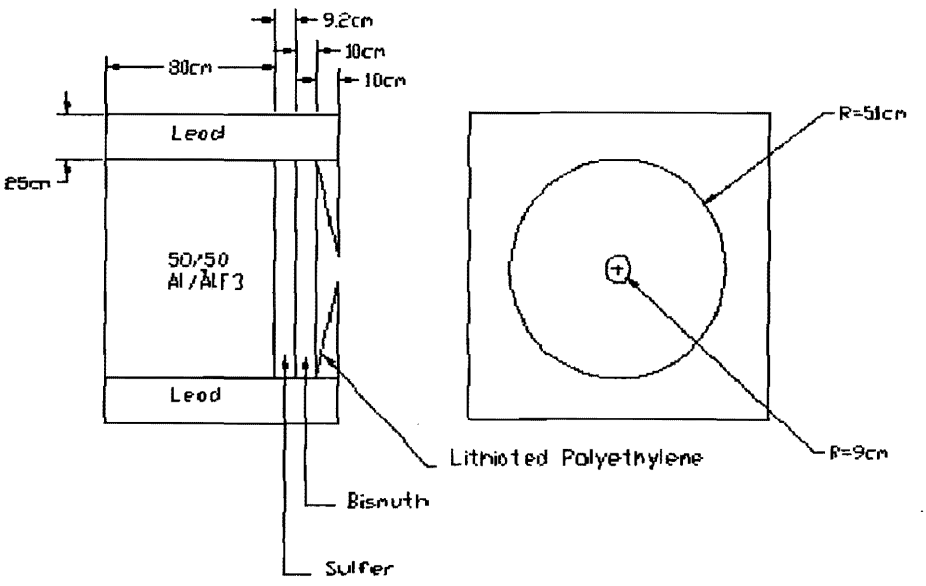


Figure 6.16 Final Collimator/Filter Design

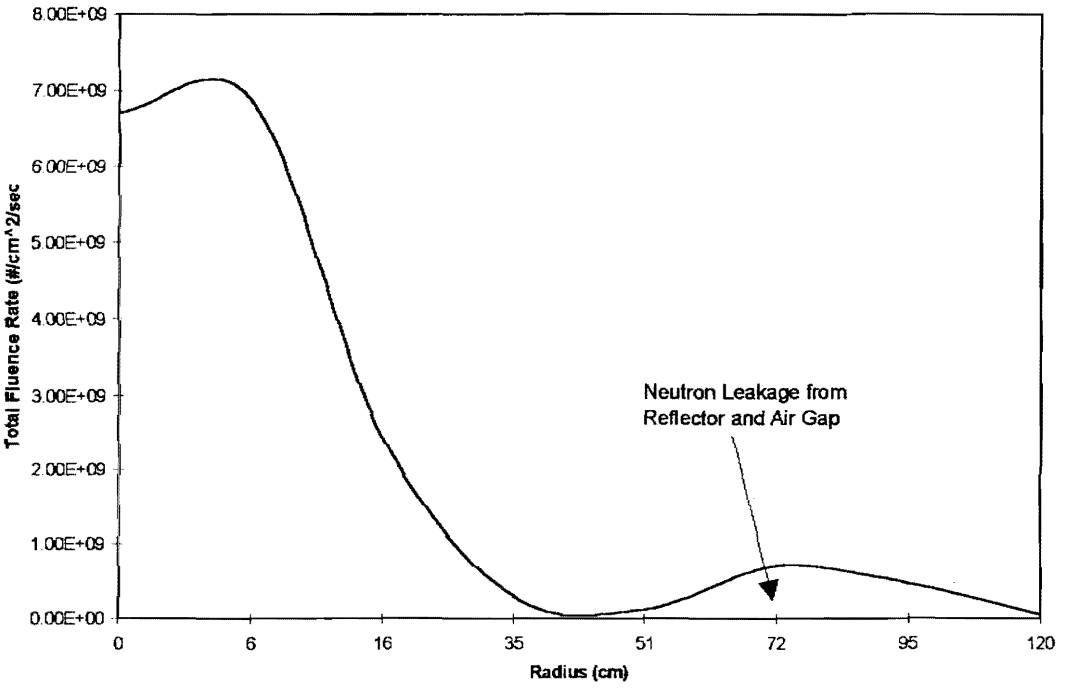


Figure 6.17 Total Fluence Rate Across Collimator

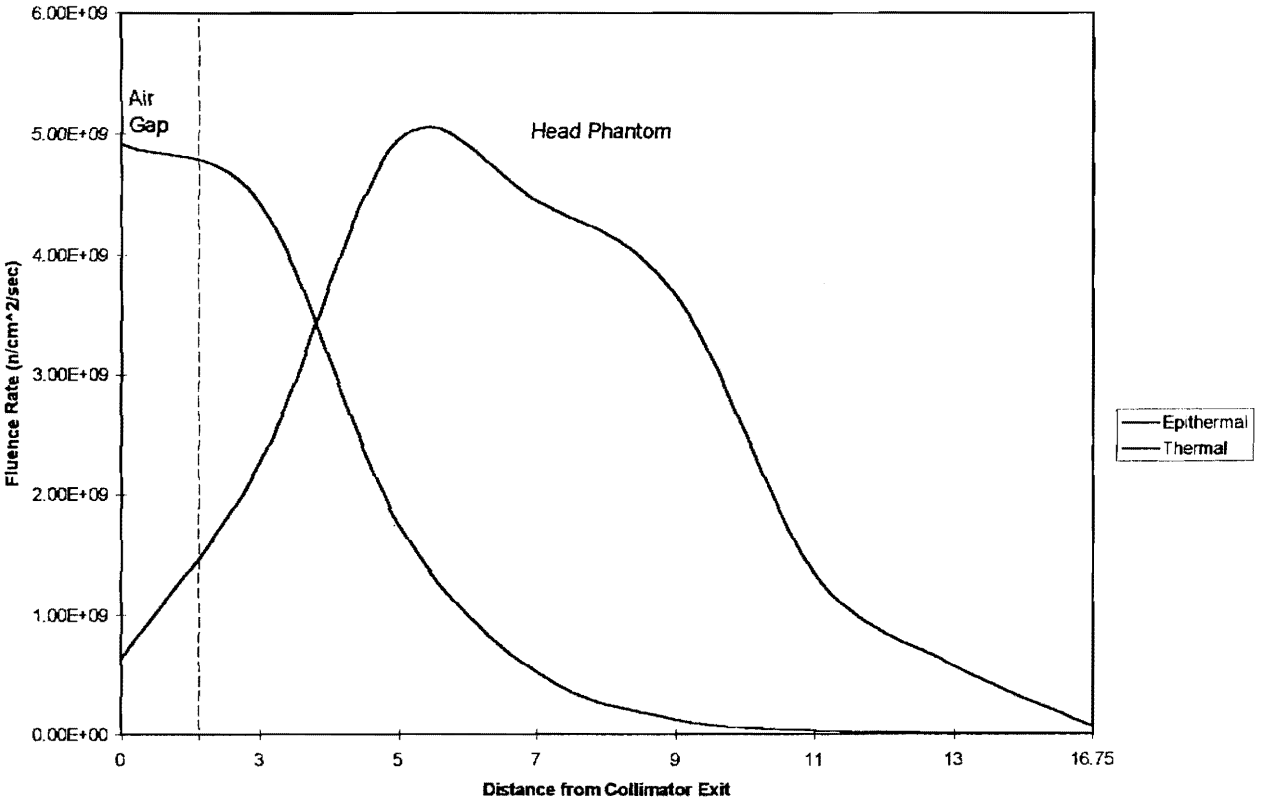


Figure 6.18 Thermal and Epithermal Penetration into the Brain

Chapter 7

Clinical Facility Design

7.1 Site Location[42]

The Tower Shielding Facility is located on a hill with an elevation of 1069 ft 2.35 miles south-southeast of Oak Ridge National Laboratory (ORNL). It is 9 miles from the city of Oak Ridge, Tennessee and 21 miles from the city of Knoxville, Tennessee. The immediate terrain on all sides of the tower structure slopes downward at the base of the towers, and the grade gradually rises to the top of Copper Ridge, approximately 400 ft to the north of the towers.

7.2 Present Tower and Facility Layout[42]

Since the TSR-II is currently classified as an unshielded reactor, the TSF is situated within a general exclusion area that is enclosed by a 6-ft-high chain-link fence topped with three strands of barbed wire.

Two reinforced-concrete underground buildings are located adjacent to and north of the towers, as shown in Figure 7.1. The smaller building is used as a service and shop area and is connected to the larger building by an 2.44 meter wide walkway. The larger building contains the reactor controls, data-collecting facility, counting room, and offices.

The buildings are shielded against radiation by an 0.46 meter thick concrete roof covered with approximately one meter of dirt.

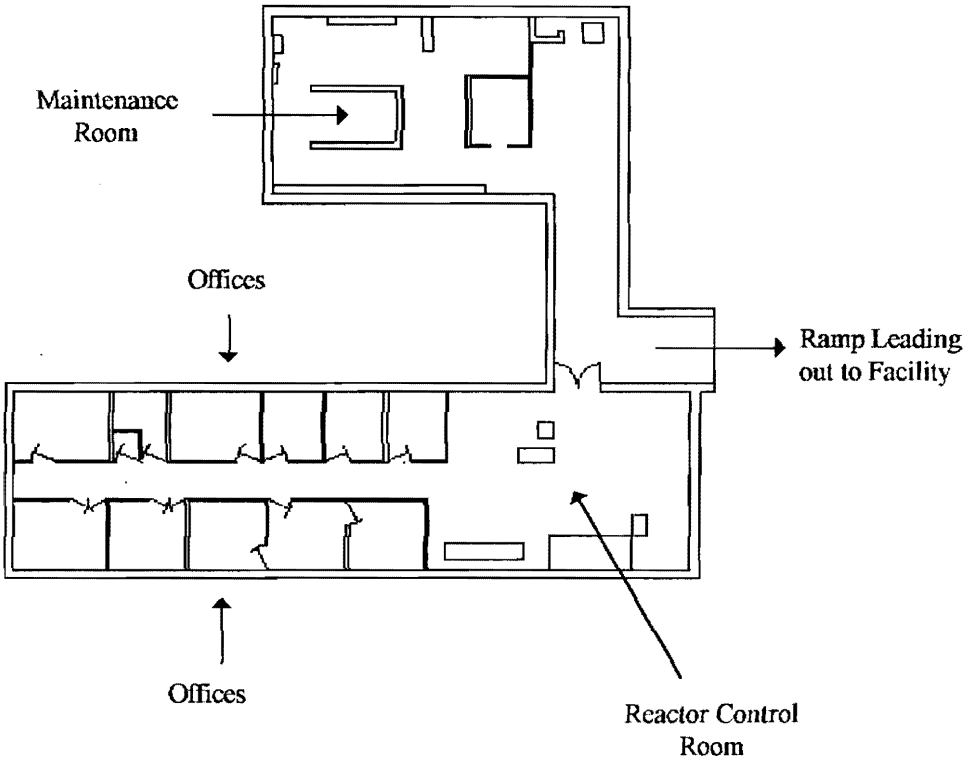


Figure 7.1. Underground Bunker

The tower structure is a braced and guyed steel frame forming a 30 meter by 61 meter rectangle, with a leg placed at each of the four corners. Each leg is 2.75 meters square, 96 meters high, and terminates at the lower end in an inverted truncated pyramid. Each pair of legs is joined at the top by a horizontal truss-type bridge running east and west. Maintenance access is provided by a bridge between legs I and IV of the north tower.

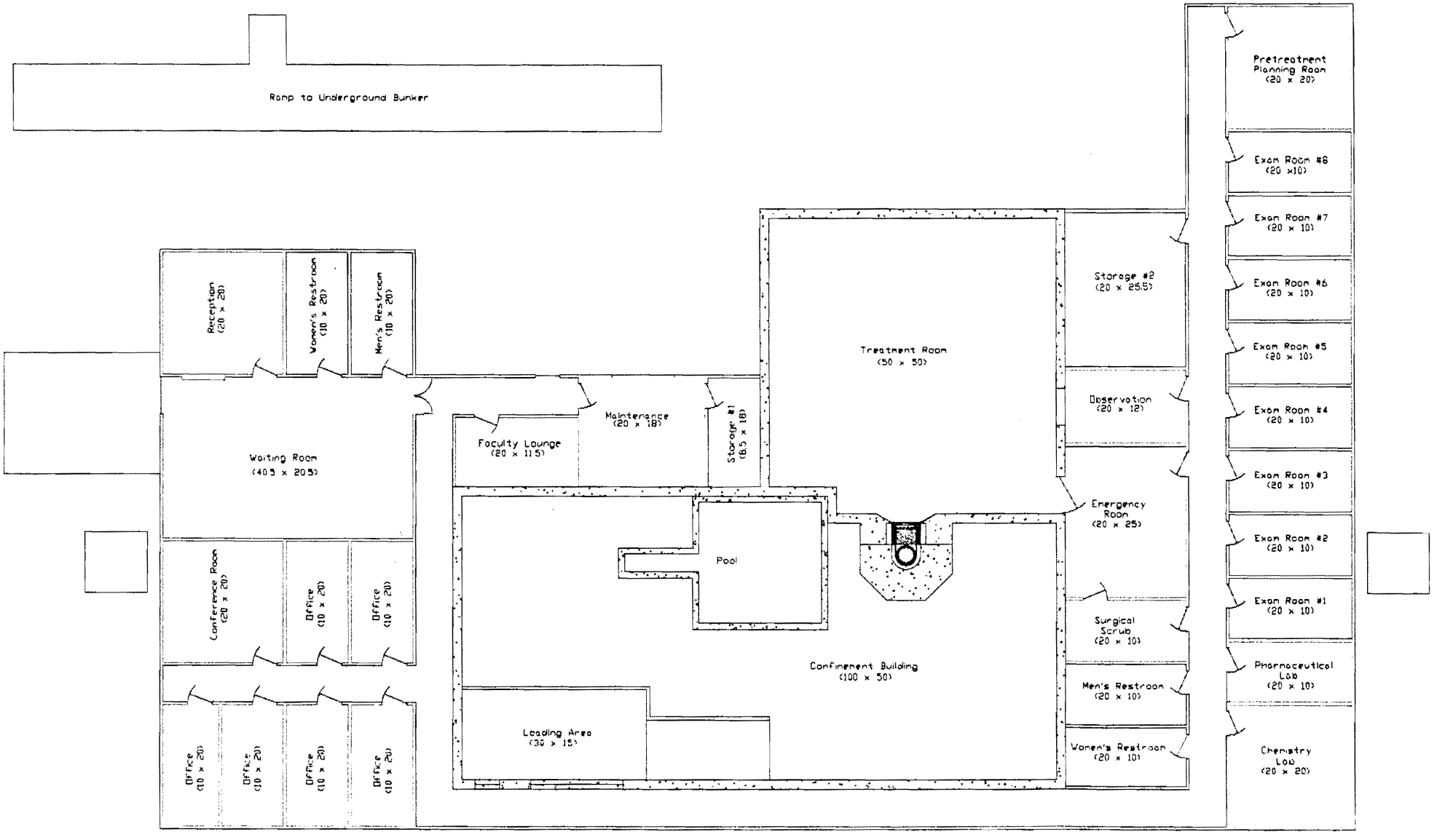
The tower structure is protected from lightning by means of a wire grounding net. A copper-clad steel-strand shielding wire is mounted on porcelain insulators to form a rectangle at a 5-ft minimum above the entire structure. Shielding wire also extends from the top of each tower to the ground to protect the inclined guys. The steel towers, the inclined guy wires, and the grounding system are connected to a buried counterpoise. The resistance to the ground of the above-ground grid system is between 1 and 3 ohms.

A two-section reinforced concrete pool provides shielding during the removal and storage of fuel elements. The pool is located midway between the west tower legs; its large section is 6.10 meters square and 7.62 meters deep. The small section of the pool is 1.22 meters wide, 3.66 meters long, and 6.71 meters deep. A guided float is installed in the pool for raising and lowering reactor shields. The water in the pool is circulated through a system of filters to keep it clear for raising the shields.

7.3 Proposed Additions

An outpatient medical facility, estimated to cost between 1.8 and 2 million dollars, will be constructed at the reactor site to house the necessary equipment for the boron neutron capture therapy, as shown in Figures 7.2 and 7.3.

Figure 7.2 Facility Layout



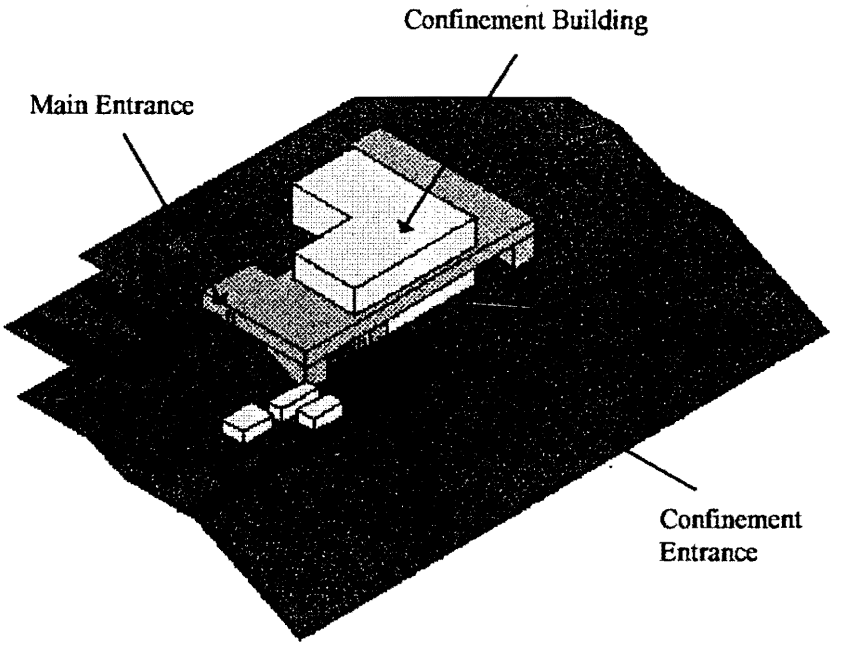


Figure 7.3. Overhead View of Facility

A confinement building, 30.48 meters long and 15.24 meters wide, with 0.45 meter thick concrete walls, is added around the reactor and pool to insure that exposure is limited to very low doses and all radioactivity is contained. A 9.14 meter long and 4.57 meter wide loading area is located in the northwest corner of the confinement building. The treatment room is 15.24 meters wide and 15.24 meters long to reduce neutron backscatter. It is located immediately adjacent to the east side of the reactor, adjoining the confinement building at the reactor porthole. The treatment room will have 0.45 meter thick concrete walls with 15 cm borated polyethylene tiles to absorb any backscatter radiation from the neutron beam. The dose rates outside of treatment room are shown in

Figure 7.4. On the south side of the treatment room will be an observation room, 6.10 meters long and 3.66 meters wide, that will allow medical personnel and the patient's family to observe the treatment.

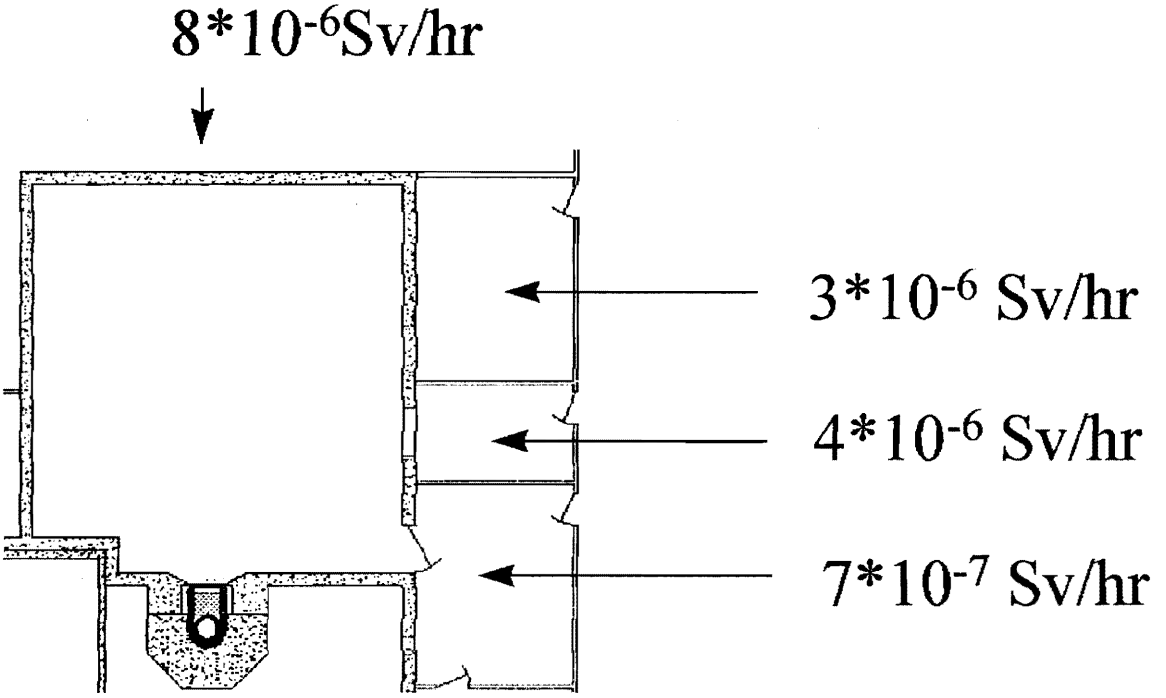


Figure 7.4 Doses Outside Treatment Room

Should an emergency in the treatment procedure arise, an emergency room, 6.10 meters long and 7.62 meters wide, will be located on the south side of the treatment room so that the patient may be taken directly from the treatment room to the emergency room. The primary emergency room equipment can be purchased for approximately $30,000. If a medical emergency occurs while the patient is in the treatment room, a surgical scrub room, 3.04 meters wide and 3.04 meters long, will be accessible to the emergency room

so that physicians may properly prepare for surgery. The cost estimates for the surgical scrub room equipment are $10,000.

A maintenance room, with dimensions of 6.10 meters long and 6.10 meters wide, will be added for electrical and mechanical support. The facility has two storage areas: one on the north side of the treatment room, connected to the maintenance room, and the other adjacent to the observation room on the south side of the treatment room. A faculty lounge, 6.10 meters long and 3.51 meters wide, is located north of the maintenance room. Six offices for physicians and technicians will be in the northwest corner of the facility, along with a conference room.[23]

7.4 Optional Thermal Treatment Room

An additional treatment room can be added into the existing facility with minor modifications to reactor and shutter assembly. Neutron leakage from the primary filter is directed through a tank of heavy water, which moderates the fast and epithermal neutrons. With 30 cm of heavy water place 97 cm from the beam centerline, as shown in Figure 7.5. The thermal neutron fluence at the exit of the heavy water filter is 1.95×10^9.

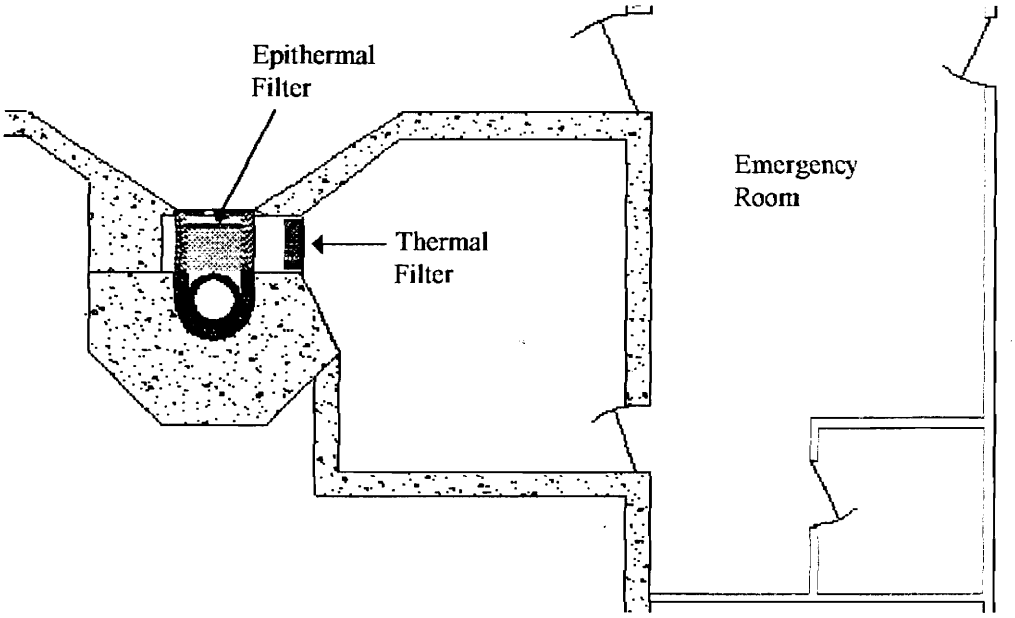


Figure 7.5 Secondary Treatment Room

7.5 Treatment Sequence

Upon arrival at the facility, the patient and his or her family enters a 12.34 meter long by 6.25 meter wide waiting room at the main entrance on the west side of the building. The patient then registers at the reception area. Restrooms are accessible from the waiting room adjacent to the reception area. The physician then directs the patient and family from the waiting room to an exam room. There are eight examination rooms, 3.05 meters wide and 6.10 meters long, located south of the emergency room. Each examination room is estimated to cost $9,000. The total price for all examination rooms is approximately $80,000, which includes a nurse call system. A technician or nurse prepares the patient for treatment, and takes any final measurements for dose calculations. These calculations are determined on computers, estimated at $70,000 each, which are

housed in the pretreatment planning room located on the southeast corner of the facility. A chemistry laboratory, 6.10 meters square, and a pharmaceutical laboratory, 6.10 meters long and 3.66 meters wide, is located west of the examination rooms and are used to quickly transfer and administer the boron pharmaceutical to the patient. After the patient has received the boron compound, he or she is transferred to the treatment room. The family can then move to the observation room or back to the waiting room. After the treatment has been completed, the patient is returned to the examination room for post-treatment observation.

7.6 Filtration System[45]

The confinement building and the treatment room have separate air filtering and ventilation systems from the rest of the facility to contain radioactive particles in the event of an emergency. To maintain the facility the two rooms have individual vacuum control systems but can share a common filtration system. Each of the vacuum control systems include two redundant fans, a differential pressure sensor, motor operated dampers, and control circuitry. Due to the need to combine the ductwork to the filtering system, the treatment room is kept at a higher pressure. If there are any leaks, or if the system should fail, the net leakage of material is directed into the confinement building and not the treatment room. The air filtration system for the confinement building and the treatment room consists of a filter unit, a centrifugal fan, and an air flow control module. The filter unit contains a demister, a relative humidity heater, a prefilter bank, HEPA filter bank, two banks of carbon absorbers in series, and another HEPA filter bank. The air flow control

unit contains a differential pressure sensor and transmitter, control circuitry, a damper actuator and two modulating dampers. The vents from this system are equipped with radiation monitoring equipment. This system creates the need to limit the recirculation of the air to the confinement building. The monitored vents in the treatment room can also act a removal system in case of an accident involving leakage of material into the treatment room and additional facility areas. This system is the mirror image of the type currently used in power producing nuclear plants, and is more than adequate to meet requirements.

7.7 Reactor Coolant System[35,42]

The existing reactor coolant system consists of a main pump that pumps demineralized water from the detention tank through an aluminum pipe into the reactor. The hot leg coming out of the reactor then goes to forced draft air radiator. In order to obtain a Class 104 license from the Nuclear Regulatory Commission, this system needs a substantial upgrade.

A flow header is placed on top the pressure vessel to provide three separate coolant loops. Each coolant loop has its own heat exchanger, with 5 m^2 of surface area, and a 7,500 W pumping system. Each added loop costs approximately $20,000. The forced air radiator is replaced with a cooling tower approximately 6 meters wide, 12 meters long, and 6 meters high at a cost of $20,000.

7.8 Future Expansion

The proposed facility is designed for outpatient treatment in order to minimize startup cost. The facility also has the capability to be expanded for additional inpatient accommodations when more revenue is desired. Long term patient rooms, a cafeteria, an X-ray room, an MRI room, a PET scan room, and additional office space can be added on the ground level as well as second and third floors. A research laboratory and facility for animal testing has also been proposed for research on other treatments, such as those for lung, breast, colon, and prostrate cancer. This facility would be in a separate building from the treatment center, so that sanitation could be assured for patients. Table 1 summarizes the cost for the facility.

Chapter 8

Conclusions

In conclusion, the optimally designed collimator yields an epithermal neutron flux of 3.44×10^{9} neutrons cm^{-2} sec^{-1} at the collimator exit, and a thermal neutron flux of 1.58×10^{9} neutrons cm^{-2} sec^{-1} at a point 7 cm into the brain. Thus, the 1 MW reactor at the Tower Shielding Facility can be utilized to generate a more optimal does than that currently being used at the 5 MW reactor at Brookhaven National Laboratory. (Epithermal neutron flux of 1.8×10^{9} neutrons cm^{-2} sec^{-1})

The conceptually designed shutter lowers the dose to 1.7×10^{-3} Sv hr^{-1} at the shutter's surface when the reactor is operating at full power.

The overall facility conceptual design incorporates all the necessary medical accommodations in an efficient, outpatient clinic. The treatment room is designed with 0.46 m thick concrete walls with a layer of 15.2 cm of borated polyethylene to minimize both the dose to adjacent rooms and the backscatter dose to the patient.

The entire conversion process and construction of the facility would cost approximately $20 million, and could generate approximately $24 million in annual revenue at an approximate cost of $80,000 per patient.

Chapter 9

Future Work

There are several design considerations that have not been mentioned thus far. These will need to be addressed in order for the conceptual design of the BNCT clinical facility at the Tower Shielding Reactor Site to be complete.

A feasibility study for a third treatment room with major structural changes will need to be made. Also, the a feasibility study of converting the facility from an out patient facility to a primary care facility that is self-sufficient needs to be performed. The current facility design must include paving and additional parking with an economic analysis of the two. A conceptual development of the second treatment room with a maximized beam must also be developed.

In the future, one must evaluate the currents, neutron kerma, and kerma at the collimator exit to generate an intensity vs. purity plot for comparison with ORNL's optimum beam.

For the optimum beam and a minimized dose at the shutter exit, codes must continued to be run. A detailed analysis of the thermal hydraulics must be performed. Finally, a more detailed economic analysis must be performed for the design to be complete.

Appendix 1[33]

Programs

A1.1 Dose

```
real flux(84),drf(84)
     character*20 xsname
     character*120 aline,aprev
     print*,' XSDRNPM output file?'
     read(*,'(a20)')xsname
     open(1,file=xsname,form='formatted',status='old')
     read(1,'(a120)')aline
C*********************************************************************
C                                                                     *
C     print *,aline                                                   *
C                                                                     *
C*********************************************************************
  10 if(aline(3:12).ne.'total flux')then
       read(1,'(a120)')aline
C*********************************************************************
C                                                                     *
C      print *,aline                                                  *
C                                                                     *
C*********************************************************************
      go to 10
     endif
     read(1,'(a120)')aline
     read(1,'(a120)')aline
     do 30 ibase=0,9
  20   if(aline(3:6).ne.'int.')then
         aprev=aline
         read(1,'(a120)')aline
C*********************************************************************
C                                                                     *
C       print *,aline                                                 *
C                                                                     *
C*********************************************************************
        go to 20
       endif
       read(aprev,'(7x,8f13.0)')(flux(ibase*8+i),i=1,8)
       read(1,'(a120)')aline
  30 continue
  40 if(aline(4:6).ne.'ela')then
       aprev=aline
       read(1,'(a120)')aline
C*********************************************************************
```

```
C                                                                       *
C     print *,aline                                                     *
C                                                                       *
C***********************************************************************
      go to 40
    endif
    read(aprev,'(7x,8f13.0)')(flux(i),i=81,84)
    call daiso('velm61.drf',1,10000)
    call daisr('drf',0,84,drf,1)
    val=0.
    do 50 i=1,84
     val=val+drf(i)*flux(i)
  50 continue
    write(*,9010)
 9010 format(/4x,'Grp.',5x,'Flux',11x,'DRF',12x,'%'/2x,
   *'======= ============ ===','=========== ==========')
 9020 format(4x,i4,2x,1pe12.5,1x,1pe14.7,1x,0pf10.4)
    do 60 i=1,84
     write(*,9020)i,flux(i),drf(i),flux(i)*drf(i)/val*100.
  60 continue
      val=val*4.24E4
    print*,' The dose rate is ',val,' mrem/hr'
    call pfstop
    stop
    end
C***********************************************************************
C***********************************************************************
    subroutine pfstop
    parameter(nscrx=10000)
    parameter(ncscrx=10000)
    character*1 zca
    common/scrch/nscr,za(nscrx),izzz1,izzzm
    common/cscrch/ncscr,zca(ncscrx),izzzcm
    ratio1=(izzzm*1.)/(nscrx*1.)*100.
    ratio2=(izzzcm*1.)/(ncscrx*1.)*100.
    write(*,9010)izzzm,nscrx,ratio1
 9010 format(/17h EXT       used ,i10,8h out of ,i10,
   *25h real/integer variables (,f8.3,2h%))
    write(*,9020)izzzcm,ncscrx,ratio2
 9020 format(12x,5h and ,i10,8h out of ,i10,12h characters ,12x,1h(,f8.
   *3,2h%)/)
    return
    end
    subroutine daiso(a200,lu,idum)                    02/19/94
C***********************************************************************
C
C Module name:
C  DAISO
C
C Called modules:
C  GTTOKE
C
C External variables - used:
```

```
C  A20                C*(
C  LU                 I*4
C
C Internal variables:
C  ALINE              C*80
C
C Variables read:
C  ALINE              C*80
C
C*******************************************************************
      parameter(ntokex=100000)
      character*32 token
      integer*4 toklen
      common/token/ntoke,token(ntokex),toklen(ntokex),irefind
      character*(*)a200
      character*20 a30,afile(10)
      character*80 aline
      integer lus(10)
      data lus/1,91,92,93,94,95,96,97,98,99/
      lus(1)=lu
      afile(1)=a200
      ifile=1
      nline=1
   10 open(lus(ifile),file=afile(ifile)(1:leng(afile(ifile),20)),
     *form='formatted',status='old')
C*******************************************************************
C
C  Read input and tokenize
C
C*******************************************************************
   20 read(lus(ifile),'(a80)',end=50)aline
      if(aline(1:8).eq.'include ')then
        do i1=9,38
          if(aline(i1:i1).ne.' ')go to 30
        enddo
   30   j=1
        a30=' '
        do i2=i1,38
          if(aline(i2:i2).eq.' ')go to 40
          a30(j:j)=aline(i2:i2)
          j=j+1
        enddo
   40   ifile=ifile+1
        if(ifile.gt.10)then
          write(*,9010)a30,afile(ifile-1)
 9010 format(/2x,'==========','==========',
     *'========'/2x,'=',54x,'='/2x,'=',5x,'DAISY input error!',31x,'='/
     *2x,'=',54x,'='/2x,'=',5x,'The include of file ',a28,1x,'='/2x,
     *'=',5x,'by file ',a28,13x,'='/2x,'=',54x,'='/2x,'=',5x,
     *'Exceeds the limit of 10 ','nested includes',10x,'='/2x,'=',54x,
     *'='/2x,'=',5x,'Halting execution.',31x,'='/2x,'=',54x,'='/2x,
     *'==========','==========','========')
          stop
```

```
      endif
      afile(ifile)=a30
      do j=1,ifile-1
       if(afile(ifile).eq.afile(j))then
        write(*,9020)afile(ifile-1),afile(j)
 9020 format(/2x,'========================','========================',
     *'========'/2x,'=',54x,'='/2x,'=',5x,'DAISY input error!',31x,'='/
     *2x,'=',54x,'='/2x,'=',5x,'File ==> ',a28,12x,'='/2x,'=',5x,
     *'includes file ',a28,7x,'='/2x,'=',54x,'='/2x,'=',5x,
     *'which is already open.',27x,'='/2x,'=',54x,'='/2x,'=',5x,
     *'Halting execution.',31x,'='/2x,'=',54x,'='/2x,
     *'========================','========================','========')
        stop
       endif
      enddo
      go to 10
     endif
     call gttoke(aline)
     nline=nline+1
     go to 20
   50 close(lus(ifile))
     ifile=ifile-1
     if(ifile.ne.0)go to 20
     nline=nline-1
     irefind=1
C**********************************************************************
C
C    Temporary write
C
C**********************************************************************
C     write(*,9030)ntoke
C 9030 format(' ntoke = ',i5)
C     write(*,9040)(i,token(i),i=1,ntoke)
C 9040 format(5x,i5,a)
     return
     end
     subroutine daisr(atitle,idfalt,nvald,val,ist)
C**********************************************************************
C
C Module name:
C  DAISR
C
C Called modules:
C  DAISF
C
C COMMON blocks:
C   token
C
C Parameters(value):
C
C External variables - used:
C  ATITLE              C*(
C  IDFALT              I*4
```

```
C  NTOKE                I*4
C  NVALD                I*4
C  TOKEN (ntokex)          C*32
C  TOKLEN (ntokex)          I*4
C  VAL (*)              C*(
C
C External variables - set:
C  TOKEN (ntokex)          C*32
C  VAL (*)              C*(
C
C Internal variables:
C  IT                  I*4
C
C Variables read:
C  VAL (*)              C*(
C
C Variables written:
C  ATITLE               C*(
C  NVALD                I*4
C  VAL (*)              C*(
C
C*********************************************************************
      parameter(ntokex=100000)
      character*32 token
      integer*4 toklen
      common/token/ntoke,token(ntokex),toklen(ntokex),irefind
      character*(*)atitle
      real val(*)
      nval=0
      if(nvald.le.0)then
        return
      endif
C*********************************************************************
C
C     call daisf(atitle,1,it)
C
C*********************************************************************
      call daisf(atitle,ist,it)
      if(it.eq.0)then
        if(idfalt.eq.1)return
        write(*,9010)atitle
 9010   format(//' DAISR ERROR - VARIABLE ',a32,' NOT FOUND')
        write(*,'(//)')
        write(99,9010)atitle
        write(99,'(//)')
        stop
      endif
   10 if(nval.ge.nvald)then
C*********************************************************************
C
C      This allows the user to put an 'E' even if the count is right
C
C*********************************************************************
```

```
      if(token(it).eq.'e')it=it+1
      return
     endif
     if(it.gt.ntoke)then
      if(idfalt.eq.0)then
       write(*,9020)atitle,nval,nvald,(ii,val(ii),ii=1,nval)
       write(*,'(//)')
       write(99,9020)atitle,nval,nvald,(ii,val(ii),ii=1,nval)
       write(99,'(//)')
 9020    format(//' DAISR ERROR - ARRAY ',a32/'    is only given ',
    *   i5,' of the ',i5,' entries required:'/(5x,i5,2x,1pe15.8))
       return
      else
       return
      endif
     endif
     if(it.ne.ntoke.and.token(it+1).eq.'=')then
      call daisf(atitle,it,it)
      if(it.eq.0)then
       if(idfalt.eq.0)then
        write(*,9020)atitle,nval,nvald,(ii,val(ii),ii=1,nval)
        write(*,'(//)')
        write(99,9020)atitle,nval,nvald,(ii,val(ii),ii=1,nval)
        write(99,'(//)')
        return
       else
        return
       endif
      endif
     endif
C*********************************************************************
C
C  Special symbol = r
C      r nrep val   repeats value VAL NREP times
C
C*********************************************************************
     if(token(it)(1:1).eq.'r')then
      if(toklen(it).eq.1)then
       it=it+1
      else
       token(it)(1:32)=token(it)(2:32)
      endif
      read(token(it),9030)nrep
      it=it+1
      read(token(it),9040)rep
      do i=1,nrep
       nval=nval+1
       val(nval)=rep
      enddo
      it=it+1
C*********************************************************************
C
C  Special symbol = f
```

```
C    f val    fills rest of field with value VAL
C
C*********************************************************************
     elseif(token(it)(1:1).eq.'f')then
      if(toklen(it).eq.1)then
        it=it+1
      else
        token(it)(1:32)=token(it)(2:32)
      endif
      read(token(it),9040)rep
      nrep=nvald-nval
      do i=1,nrep
        nval=nval+1
        val(nval)=rep
      enddo
      it=it+1
C*********************************************************************
C
C  Special symbol = e
C    e  Does not bother rest of field  (Allows programmer to
C       initialize input values to defaults)
C
C*********************************************************************
     elseif(token(it).eq.'e')then
      nval=nvald
      it=it+1
C*********************************************************************
C
C  Special symbol = i
C    val1 i nint val2   = Interpolates NINT values between VAL1
C                         and VAL2 (results in NINT+2 entries)
C
C*********************************************************************
     elseif(token(it)(1:1).eq.'i')then
      if(toklen(it).eq.1)then
        it=it+1
      else
        token(it)(1:32)=token(it)(2:32)
      endif
      read(token(it),9030)nint
      it=it+1
      read(token(it),9040)val2
      val1=val(nval)
      do i=1,nint
        nval=nval+1
        val(nval)=val1+(val2-val1)*i/(nint+1.0)
      enddo
      nval=nval+1
      val(nval)=val2
      it=it+1
C*********************************************************************
C
C  Special symbol = l
```

```
C   val1 l nint val2   = Interpolates NINT values between VAL1
C                        and VAL2 (results in NINT+2 entries)
C
C*********************************************************************
     elseif(token(it).eq.'l')then
       it=it+1
      read(token(it),9030)nint
      it=it+1
      read(token(it),9040)val2
      val1=val(nval)
      do i=1,nint
       nval=nval+1
c       val(nval)=val1+(val2-val1)*i/(nint+1.0)
       val(nval)=val1*exp(alog(val2/val1)*i/(nint+1.0)
      enddo
      nval=nval+1
      val(nval)=val2
      it=it+1
C*********************************************************************
C
C  Special symbol = m
C   m nint val1 val2   = Delivers the midpoints of NINT regions
C                        between VAL1 and VAL2 (results in NINT
C                        entries)
C
C*********************************************************************
     elseif(token(it)(1:1).eq.'m')then
      if(toklen(it).eq.1)then
       it=it+1
      else
       token(it)(1:32)=token(it)(2:32)
      endif
      read(token(it),9030)nint
      it=it+1
      read(token(it),9040)val1
      it=it+1
      read(token(it),9040)val2
      dval=(val2-val1)/float(nint)
      val1=val1-dval*0.5
      do i=1,nint
       nval=nval+1
       val1=val1+dval
       val(nval)=val1
      enddo
      it=it+1
     else
      nval=nval+1
      read(token(it),9040)val(nval)
9030   format(bn,i20)
9040   format(bn,f20.0)
      it=it+1
     endif
     go to 10
```

```
      end
C*********************************************************************
C*********************************************************************
      subroutine daisf(atitle,ist,it)
C*********************************************************************
C
C Module name:
C   DAISF
C
C Called by:
C   DAISC  DAISI  DAISR
C
C Parameters(value):
C
C External variables - used:
C   ATITLE                C*(
C   IST                 I*4
C   NTOKE                 I*4
C   TOKEN (ntokex)          C*32
C
C External variables - set:
C   IT                  I*4
C
C*********************************************************************
      parameter(ntokex=100000)
      character*32 token
               integer*4 toklen
           common/token/ntoke,token(ntokex),toklen(ntokex),irefind
      parameter(nequalx=3000)
      character*(*)atitle
      character*32 cleft
      common/equals/nequal,iequals(nequalx)
      if(irefind.eq.1)then
       irefind=0
       nequal=0
       do i=1,ntoke
        if(token(i).eq.'=')then
         nequal=nequal+1
         iequals(nequal)=i
        endif
       enddo
      endif
      do ie=1,nequal
       if(iequals(ie).ge.ist)go to 10
      enddo
      it=0
      return
   10 do j=ie,nequal
        i=iequals(j)
        if(token(i-1).eq.atitle)then
         it=i+1
         return
        endif
```

```
      enddo
      it=0
      return
      end
C*********************************************************************
C*********************************************************************
      subroutine gttoke(aline)                          gttoke 1
C*********************************************************************
C
C Module name:
C   GTTOKE
C
C Called by:
C   DAISO
C
C COMMON blocks:
C    token
C
C Parameters(value):
C
C External variables - used:
C   ALINE                C*80
C
C External variables - set:
C   NTOKE                I*4
C   TOKEN (ntokex)         C*32
C   TOKLEN (ntokex)        I*4
C
C*********************************************************************
      parameter(ntokex=100000)
      character*32 token
      character*80 aline
      integer*4 toklen
      common/token/ntoke,token(ntokex),toklen(ntokex),irefind
      data ifirst/1/
      if(ifirst.eq.1)then
        ifirst=0
        ntoke=0
      endif
      nchar=80
C*********************************************************************
C
C  TOKLEN = Length of token in characters
C
C*********************************************************************
C
C Find the first and last non-delimitors
C
C*********************************************************************
      do icol=1,nchar
        ich=ichar(aline(icol:icol))
C*********************************************************************
C
```

```
C    The delimitors are blank, comma, =, and TAB
C
C*********************************************************************
      if(ich.ne.9.and.ich.ne.32.and.ich.ne.61.and.ich.ne.44)then
       do iend=nchar,icol,-1
        ich=ichar(aline(icol:icol))
        if(ich.ne.9.and.ich.ne.32.and.ich.ne.61.and.ich.ne.44)go
     *     to 10
       enddo
      endif
     enddo
C*********************************************************************
C
C   The statement is blank.  Return
C
C*********************************************************************
     go to 30
   10 ic=icol-1
C*********************************************************************
C
C   1. Locate the next delimitor.
C
C*********************************************************************
   20 ic=ic+1
     if(ic.gt.iend)then
C*********************************************************************
C
C     A. If you run out of characters, package those you have into
C        a type 2 token
C
C*********************************************************************
      if(aline(icol:icol).eq.'!')go to 30
      ntoke=ntoke+1
      toklen(ntoke)=iend-icol+1
      token(ntoke)=aline(icol:iend)
      go to 30
     endif
     ich=ichar(aline(ic:ic))
C*********************************************************************
C
C    The delimitors are blank, comma, =, and TAB
C
C*********************************************************************
     if(ich.eq.9.or.ich.eq.32.or.ich.eq.61.or.ich.eq.44)then
C*********************************************************************
C
C   2. Package the previous characters (if there are any) into
C        a type 2 token
C
C*********************************************************************
      if(icol.ne.ic)then
       if(aline(icol:icol).eq.'!')go to 30
       ntoke=ntoke+1
```

```
        toklen(ntoke)=ic-icol
        token(ntoke)=aline(icol:ic-1)
      endif
C*********************************************************************
C
C     If it was an equal sign, add a token with the equal in it
C
C*********************************************************************
      if(ich.eq.61)then
        ntoke=ntoke+1
        token(ntoke)='='
        toklen(ntoke)=1
      endif
C*********************************************************************
C
C  3. Find the next non-blank and set as ICOL
C
C*********************************************************************
      do icol=ic+1,iend
C*********************************************************************
C
C     A. If all went well, loop back to 1.
C
C*********************************************************************
        if(aline(icol:icol).ne.' ')then
          ic=icol-1
          go to 20
        endif
      enddo
C*********************************************************************
C
C     B. If you run out of characters, return
C
C*********************************************************************
      go to 30
    endif
C*********************************************************************
C
C   Keep collecting characters
C
C*********************************************************************
    go to 20
  30 return
    end
C*********************************************************************
C*********************************************************************
    function leng(a,lim)
C*********************************************************************
C
C Module name:
C   LENG
C
C External variables - used:
```

```
C  A                                        C*64
C  LIM                                       I*4
C
C Internal variables:
C  LENG                                      I*4
C
C*********************************************************************
      character*1 a(*)
      do leng=lim,1,-1
        if(a(leng).ne.' '.and.a(leng).ne.char(9))return
      enddo
      leng=0
      return
      end
```

A1.2 DRIP

```
program drip
      character*8 hname,huse(2)
      character*8 date,user,charge,case,time
      character*8 titl(12)
      character*60 file1
C*********************************************************************
C                                                                     *
C     Reads DORT output in the VARFLM format                          *
C                                                                     *
C*********************************************************************
      write(*,9010)
 9010 format(/6x,'What is the DORT flux ou','tput file name?'/)
      read(*,'(a60)')file1
open(3,file=file1,status='old',form='unformatted')
      open(1,file='dortread.out',status='unknown',form='formatted')
      open(2,file='dortread.dos',status='unknown',form='formatted')
C*********************************************************************
C                                                                     *
C     Read FILE IDENTIFICATION                                        *
C                                                                     *
C*********************************************************************
      read(3)hname,(huse(i),i=1,2),ivers
      write(1,9020)hname,(huse(i),i=1,2),ivers
 9020 format(12x,'File name ==> ',a8/2x,'User identification ==> ',a6,
     *a6/9x,'File version ==> ',i6)
C*********************************************************************
C                                                                     *
C    Read FILE LABEL                                                  *
C                                                                     *
C*********************************************************************
      read(3)date,user,charge,case,time,(titl(i),i=1,12)
      write(1,9030)date,user,charge,case,time,(titl(i),i=1,12)
      write(2,9040)date,user,charge,case,time,(titl(i),i=1,12)
 9030 format(/8x,'Date ==> ',a8/8x,'User ==> ',a8/6x,'Charge ==> ',a8/
     *8x,'Case ==> ',a8/8x,'Time ==> ',a8//1x,'Title ==>'/2x,a6,a6,a6,
     *a6,a6,a6,a6,a6,a6,a6,a6,a6,a4/)
 9040 format('!',8x,'date ==> ',a8/'!',8x,'user ==> ',a8/'!',6x,
     *'charge ==> ',a8/'!',8x,'case ==> ',a8/'!',8x,'time ==> ',a8/'!'/
     *'! title ==>'/'! ',a6,a6,a6,a6,a6,a6,a6,a6,a6,a6,a6,a4)
C*********************************************************************
C                                                                     *
C     Read FILE CONTROL                                               *
C                                                                     *
C*********************************************************************
      read(3)igm,neut,jm,lm,ima,mma,ism,imsism,isbt,iter,(idum,i=1,15)
      write(1,9050)igm,neut,jm,lm,ima,mma,ism,imsism,isbt,iter
      write(2,9060)igm,neut,jm,lm,ima,mma,ism,imsism,isbt,iter
 9050 format(21x,'No. of energy groups ==>',1x,i6/23x,
     *'Last neutron group ==> ',i6/20x,'Number of J intervals ==','> ',
     *i6/7x,'Maximum length of moment',1x,'expansion ==> ',i6/20x,
     *'Number of I intervals ==','> ',i6/12x,
```

```
     *'Number of boundary direc','tions ==> ',i6/16x,
     *'Number of I-boundary set','s ==> ',i6/14x,
     *'Total number of I-interv','als ==> ',i6/14x,
     *'I-set for system boundar','ies ==> ',i6/2x,
     *'Outer iteration no. when',1x,'fluxes written ==> ',i6)
 9060 format('!'/'!',21x,'no. of energy groups ==>',1x,i6/'!',23x,
     *'last neutron group ==> ',i6/'!',20x,'number of j intervals ==',
     *'> ',i6/'!',7x,'maximum length of moment',1x,'expansion ==> ',i6/
     *'!',20x,'number of i intervals ==','> ',i6/'!',12x,
     *'number of boundary direc','tions ==> ',i6/'!',16x,
     *'number of i-boundary set','s ==> ',i6/'!',14x,
     *'total number of i-interv','als ==> ',i6/'!',14x,
     *'i-set for system boundar','ies ==> ',i6/'!',2x,
     *'outer iteration no. when',1x,'fluxes written ==> ',i6)
     write(2,9070)igm,neut,jm,mma
 9070 format(/'!'/'! IGM is number of energ','y groups'/'!',2x,
     *'MMA is number of angles'/'!'/1x,'igm = ',i5/1x,
     *'last_neutron_group = ',i5/1x,'nz = ',i5/1x,'mma = ',i5)
     call doit(igm,ism,jm,mma,isbt,neut)
     call pfstop
     stop
     end
C*************************************************************************
C*************************************************************************
     subroutine doit(igm,ism,jm,mma,isbt,neut)
     parameter(nscrx=300000)
     parameter(ncscrx=10000)
     character*1 zca
     common/scrch/nscr,za(nscrx),izzz1,izzzm
     common/cscrch/ncscr,zca(ncscrx),izzzcm
     data ifirst/1/
     nscr0=nscr
     ncscr0=ncscr
     klmbig=ialc8((igm),'lmbig      ')
     kimbis=ialc8((ism),'imbis      ')
     kiset=ialc8((jm),'iset       ')
     kz=ialc8((jm+1),'z          ')
     kr=ialc8((3000)*(ism),'r          ')
     call zdoit(igm,ism,jm,mma,isbt,neut,za(klmbig),za(kimbis),za(
    *kiset),za(kz),za(kr))
     nscr=nscr0
     ncscr=ncscr0
     return
     end
C*************************************************************************
C*************************************************************************
     subroutine zdoit(igm,ism,jm,mma,isbt,neut,lmbig,imbis,iset,z,r)
     integer lmbig(*),imbis(*),iset(*)
     real z(*),r(3000,*)

     character*60 file1
C*************************************************************************
C                                                                       *
```

```
C     Read FILE INTEGER PARAMETERS                                      *
C        (Will not print because I do not use them)                     *
C                                                                       *
C***********************************************************************
      read(3)(lmbig(ig),ig=1,igm),(imbis(is),is=1,ism),(iset(j),j=1,jm)
      lmbigx=0
      do 10 ig=1,igm
       if(lmbig(ig).gt.lmbigx)lmbigx=lmbig(ig)
   10 continue
      imbisx=0
      do 20 i=1,igm
       if(imbis(i).gt.imbisx)imbisx=imbis(i)
   20 continue
      write(2,9010)imbis(isbt)
 9010 format(2x,'nr = ',i5)
C***********************************************************************
C                                                                       *
C     Read FILE REAL PARAMETERS                                         *
C                                                                       *
C***********************************************************************
      read(3)(z(j),j=1,jm+1),((r(i,is),i=1,imbis(is)+1),is=1,ism),(
     *ener,ig=1,igm),emin,cneut,ev,devdk,effk,power,(dumrl,i=1,13)
      write(2,9020)(z(i),i=1,jm+1)
 9020 format(1x,'z ='/(1x,0pf9.4,1x,0pf9.4,1x,0pf9.4,1x,0pf9.4,1x,
     *0pf9.4,1x))
      write(2,9030)(r(i,isbt),i=1,imbis(isbt)+1)
 9030 format(1x,'r ='/(1x,0pf9.4,1x,0pf9.4,1x,0pf9.4,1x,0pf9.4,1x,
     *0pf9.4,1x))
      write(*,9040)
 9040 format(/3x,'What is the input file t','hat contains the (r,z) p',
     *'oints desired?'/)
      read(*,'(a60)')file1
      call daiso(file1,1,10000)
      call dcount('points',ndes,1)
      ndes=ndes/2
      call rdflux(igm,jm,imbisx,imbis,iset,mma,isbt,neut,r,z,ndes)
      return
      end
C***********************************************************************
C***********************************************************************
      subroutine rdflux(igm,jm,imbisx,imbis,iset,mma,isbt,neut,r,z,
     *                  ndes)
      parameter(nscrx=300000)
      parameter(ncscrx=10000)
      character*1 zca
      common/scrch/nscr,za(nscrx),izzz1,izzzm
      common/cscrch/ncscr,zca(ncscrx),izzzcm
      data ifirst/1/
      nscr0=nscr
      ncscr0=ncscr
      kflum=ialc8((imbisx)*(jm)*(igm),'flum      ')
      kdose=ialc8((imbisx)*(jm)*(3),'dose      ')
      kdneut=ialc8((igm),'dneut      ')
```

```
      kfdose=ialc8((igm),'fdose      ')
      kden=ialc8((imbisx)*(jm),'den        ')
      kzdes=ialc8((ndes),'zdes       ')
      krdes=ialc8((ndes),'rdes       ')
      kpoints=ialc8((ndes*2),'points     ')
      kides=ialc8((ndes),'ides       ')
      kjdes=ialc8((ndes),'jdes       ')
      call zrdflux(igm,jm,imbisx,imbis,iset,mma,isbt,neut,r,z,ndes,za(
     *kflum),za(kdose),za(kdneut),za(kfdose),za(kden),za(kzdes),za(
     *krdes),za(kpoints),za(kides),za(kjdes))                    rdflux 2
      nscr=nscr0
      ncscr=ncscr0
      return
      end
C*********************************************************************
C*********************************************************************
      subroutine zrdflux(igm,jm,imbisx,imbis,iset,mma,isbt,neut,r,z,
     *                ndes,flum,dose,dneut,fdose,den,zdes,rdes,
     *                points,ides,jdes)
      real flum(imbisx,jm,*),dose(imbisx,jm,*)
      real dneut(*),fdose(*),den(imbisx,*)
      real zdes(*),rdes(*),points(*)
      integer ides(*),jdes(*)

      character*32 drf
      character*60 file1
      character*80 file,title
      real r(*),z(*),r0(2),z0(2)
      integer imbis(*),iset(*)
      call daisr('points',0,ndes*2,points,1)
      do 10 i=1,ndes
        rdes(i)=points(2*i-1)
        zdes(i)=points(2*i)
   10 continue
      do 20 i=1,igm
        dneut(i)=1.
   20 continue
C*********************************************************************
C                                                                    *
C    THE NEXT FACTOR IS A HARDWIRED SCALING FACTOR                   *
C                                                                    *
C*********************************************************************

      fact= ((91.3*91.3)/(53.66*53.66))*(16666.67)

      write(*,9010)
 9010 format(/3x,'What is the file name fo','r the dose response func',
     *'tions?'/)
      read(*,'(a60)')file1
      if(file1.ne.'')then
        call dclear
        call daiso(file1,1,10000)
        call daisr('drf',0,igm,dneut,1)
```

```
      else
       print*,'  What group do you want?'
       read(*,'(bn,i10)')igdes
       do 30 i=1,igm
        dneut(i)=0
   30  continue
       dneut(igdes)=1.
      endif
      do 50 i=1,imbisx
       do 40 j=1,jm
        dose(i,j,1)=0.
        dose(i,j,2)=0.
   40  continue
   50 continue
C*********************************************************************
C                                                                    *
C    Read SCALAR FLUX MOMENTS                                        *
C                                                                    *
C*********************************************************************
      imb=imbis(isbt)

      do 90 ig=1,igm
       print*,' Group ',ig
       do 80 j=1,jm
        is=iset(j)
        ims=imbis(is)
        read(3)(flum(i,j,ig),i=1,ims)
        do 60 i=1,ims
         flum(i,j,ig)=flum(i,j,ig)*fact
   60   continue
        do 70 i=1,ims
         if(ig.le.neut)then
          dose(i,j,1)=dose(i,j,1)+flum(i,j,ig)*dneut(ig)
         else
          dose(i,j,2)=dose(i,j,2)+flum(i,j,ig)*dneut(ig)
         endif
   70   continue

 9020    format(2x,i3,2x,i3,1x,i3,2x,2pe15.8)
   80  continue
       read(3)
   90 continue
      write(2,9030)(imbis(iset(j)),j=1,jm)
 9030 format('!'/'!',3x,'Scalar dose in format'/'!'/'!',6x,
     *'((dose(i,j),i=1,imbis(j)','),j=1,jm)'/'!'/'!',6x,
     *'where the IMBIS are the ','number of I nodes'/'!',8x,
     *'per J level'/'!'/'!',4x,'Here are the IMBIS value','s -'/'!'/5x,
     *'imbis ='/(1x,i4,1x,i4,1x,i4,1x,i4,1x,i4,1x,i4,1x,i4,1x,i4,1x,i4,1x,i4,
     *1x,i4,1x))
      write(2,9040)
 9040 format('!'/'!',3x,'Neutron scalar doses -'/'!'/2x,'n_dose =')
      do 100 j=1,jm
       zmid=0.5*(z(j)+z(j+1))
```

```
      write(2,9050)zmid,(dose(i,j,1),i=1,imbis(iset(j)))
  100 continue
 9050 format('!',2x,'Height = ',0pf12.5/(1x,2pe11.4,1x,2pe11.4,1x,
     *2pe11.4,1x,2pe11.4,1x,2pe11.4))
      write(2,9060)
 9060 format('!'/'!',3x,'Gamma scalar doses -'/'!'/2x,'g_dose =')
      do 110 j=1,jm
       zmid=0.5*(z(j)+z(j+1))
       write(2,9050)zmid,(dose(i,j,2),i=1,imbis(iset(j)))
  110 continue
C*************************************************************************
C                                                                        *
C    Combine neutron and gamma into a total dose                         *
C                                                                        *
C*************************************************************************
      do 130 j=1,jm
       do 120 i=1,imbis(iset(j))
        dose(i,j,3)=dose(i,j,1)+dose(i,j,2)
  120  continue
  130 continue
C*************************************************************************
C                                                                        *
C    For each of the desired points                                      *
C                                                                        *
C*************************************************************************
      nz=jm
      nr=imbisx
      do 210 id=1,ndes
       write(*,9070)id,rdes(id),zdes(id)
 9070  format(/'=======================','=======================',
     * '==============='//3x,'Desired point #',i4,2x,'(',0pf9.4,',',
     * 0pf9.4,')'/)
C*************************************************************************
C                                                                        *
C      Find the (i,j) point                                              *
C                                                                        *
C*************************************************************************
       if(rdes(id).lt.r(1).or.rdes(id).gt.r(nr+1))then
        write(*,9080)rdes(id),r(1),r(nr+1)
 9080    format(/2x,'Listen, you dummy!',3x,'The desired R point, ',
     *   0pf9.5/4x,'is outside the data rang','e ==> (',0pf9.5,', ',
     *   0pf7.3,')'//5x,'Ignoring that point...'/)
        go to 200
       endif
       if(zdes(id).lt.z(1).or.zdes(id).gt.z(nz+1))then
        write(*,9090)zdes(id),z(1),z(nz+1)
 9090    format(/2x,'Listen, you dummy!',3x,'The desired Z point, ',
     *   0pf9.5/4x,'is outside the data rang','e ==> (',0pf9.5,', ',
     *   0pf7.3,')'//5x,'Ignoring that point...'/)
        go to 200
       endif
       do 140 ir=1,nr
        if(rdes(id).lt.r(ir+1))go to 150
```

```
 140  continue
 150  i=ir
      do 160 iz=1,nz
       if(zdes(id).lt.z(iz+1))go to 170
 160  continue
 170  j=iz
      write(*,9100)i,j
9100  format(/9x,'The point is in cell (',i4,',',i4,')'/)
C*************************************************************************
C                                                                        *
C     Print the table                                                    *
C                                                                        *
C*************************************************************************
      tdos=0.
      do 180 ig=1,igm
       fdose(ig)=flum(i,j,ig)*dneut(ig)
       tdos=tdos+fdose(ig)
 180  continue
      write(*,9110)
      do 190 ig=1,igm
       perc=fdose(ig)/tdos*100.
       if(perc.gt.0.)write(*,9120)ig,flum(i,j,ig),fdose(ig),perc
9110   format(/9x,'Group',5x,'Flux',10x,'Dose',9x,'%'/9x,
     *  '===== ============= ====','========== ======')
9120   format(9x,i4,2x,1pe13.6,1x,1pe14.7,1x,0pf6.2)
 190  continue
 200  continue
 210 continue
C*************************************************************************
C                                                                        *
C    Make the dose map                                                   *
C                                                                        *
C*************************************************************************
     print*,'  What do you want the .PS dos','e file to be?'
     read(*,'(a30)')file
     title='Dose map for file '//file(1:30)
     nx0=1
     ny0=1
     r0(1)=r(1)
     r0(2)=r(nr+1)
     z0(1)=z(1)
     z0(2)=z(nz+1)
     do 230 i=1,nr
      do 220 j=1,nz
       den(i,j)=alog(dose(i,j,3))
 220  continue
 230 continue
     call makeps(r0,z0,nx0,ny0,den,r,z,nr,nz,title,file,1)
     return
     end
C*************************************************************************
C*************************************************************************
     subroutine makeps(x0,y0,nx0,ny0,den,x,y,nx,ny,title,file,inorm)
```

```
      parameter(nscrx=300000)
      parameter(ncscrx=10000)
      character*1 zca
      common/scrch/nscr,za(nscrx),izzz1,izzzm
      common/cscrch/ncscr,zca(ncscrx),izzzcm
      data ifirst/1/
      nscr0=nscr
      ncscr0=ncscr
      kcolor=ialc8((nx)*(ny),'color      ')
      call zmakeps(x0,y0,nx0,ny0,den,x,y,nx,ny,title,file,inorm,za(
     *kcolor))
      nscr=nscr0
      ncscr=ncscr0
      return
      end
C*********************************************************************
C*********************************************************************
      subroutine zmakeps(x0,y0,nx0,ny0,den,x,y,nx,ny,title,file,inorm,
     *                   color)
      real color(nx,*)

      real x0(nx0+1),y0(ny0+1)
      real x(nx+1),y(ny+1),den(nx,ny)
      character*80 title,file,aline
C*********************************************************************
C                                                                    *
C     Sort the material densities                                    *
C                                                                    *
C*********************************************************************
      wtmax=-1000000000.
      do 20 j=1,ny
        do 10 i=1,nx
          if(den(i,j).gt.wtmax)wtmax=den(i,j)
   10   continue
   20 continue
      if(inorm.eq.0)then
        wtmin=0.
      else
        wtmin=1000000000.
        do 40 j=1,ny
          do 30 i=1,nx
            if(den(i,j).lt.wtmin)wtmin=den(i,j)
   30     continue
   40   continue
      endif
      if(wtmax.le.wtmin)wtmax=wtmin+1.
      do 60 j=1,ny
        do 50 i=1,nx
          frac=(den(i,j)-wtmin)/(wtmax-wtmin)
          color(i,j)=1.-frac
   50   continue
   60 continue
C*********************************************************************
```

```
C                                                                       *
C    Initialize the DRAW subroutines                                    *
C                                                                       *
C***********************************************************************
     call drbegin(x0(1),y0(1),x0(nx0+1),y0(ny0+1),title,file)
C***********************************************************************
C                                                                       *
C    Draw the calculational cells                                       *
C                                                                       *
C***********************************************************************
     call drthick(.001)
     call drtype('dashed')
     do 80 j=1,ny
       do 70 i=1,nx
         call drfbox(x(i),y(j),x(i+1),y(j+1),color(i,j))
  70   continue
  80 continue
     call drtype('solid')
C***********************************************************************
C                                                                       *
C    Draw the bounding box                                              *
C                                                                       *
C***********************************************************************
     call drbox(x0(1),y0(1),x0(nx0+1),y0(ny0+1))
C***********************************************************************
C                                                                       *
C    Draw the boxes of original mesh                                    *
C                                                                       *
C***********************************************************************
     density=1.
     do 100 i=1,nx0
       do 90 j=1,ny0
         jj=ny0+1-j
         call drbox(x0(i),y0(j),x0(i+1),y0(j+1))
  90   continue
 100 continue
C***********************************************************************
C                                                                       *
C    End the DRAW subroutine set                                        *
C                                                                       *
C***********************************************************************
     call drend
     aline='ghostview '//file(1:leng(file,32))//' &'
     call system(aline)
     return
     end
C***********************************************************************
C***********************************************************************
     function ialc8(nn,avar)
     character*12 avar
     parameter(nscrx=300000)
     parameter(ncscrx=10000)
     character*1 zca
```

```
      common/scrch/nscr,za(nscrx),izzz1,izzzm
      common/cscrch/ncscr,zca(ncscrx),izzzcm
      if(nscr.eq.0)then
        nscr=1
        izzz1=1
        izzzm=1
      endif
      ialc8=nscr
      nscr=nscr+nn
      if(nscr.gt.nscrx)then
        write(*,9010)avar,nn,nscr
 9010   format(31h No more REAL/INT scratch room.,7h   Var ,a,6h Leng ,
     *  i9,13h Requested = ,i9)
        stop
      endif
      if(nscr.gt.izzzm)izzzm=nscr
      return
      end
C*************************************************************************
C*************************************************************************
      function icalc8(nn)
      parameter(nscrx=300000)
      parameter(ncscrx=10000)
      character*1 zca
      common/scrch/nscr,za(nscrx),izzz1,izzzm
      common/cscrch/ncscr,zca(ncscrx),izzzcm
      if(ncscr.eq.0)then
        ncscr=1
        izzzcm=1
      endif
      icalc8=ncscr
      ncscr=ncscr+nn
      if(ncscr.gt.ncscrx)then
        write(*,9010)
 9010   format(50h  There is not enough CHAR scratch room. Stopping.)
        stop
      endif
      if(ncscr.gt.izzzcm)izzzcm=ncscr
      return
      end
C*************************************************************************
C*************************************************************************
      subroutine pfstop
      parameter(nscrx=300000)
      parameter(ncscrx=10000)
      character*1 zca
      common/scrch/nscr,za(nscrx),izzz1,izzzm
      common/cscrch/ncscr,zca(ncscrx),izzzcm
      ratio1=(izzzm*1.)/(nscrx*1.)*100.
      ratio2=(izzzcm*1.)/(ncscrx*1.)*100.
      write(*,9010)izzzm,nscrx,ratio1
 9010 format(/17h DORTREAD   used ,i10,8h out of ,i10,
     *25h real/integer variables (,f8.3,2h%))
```

```
      write(*,9020)izzzcm,ncscrx,ratio2
 9020 format(12x,5h and ,i10,8h out of ,i10,12h characters ,12x,1h(,f8.
     *3,2h%)/)
      return
      end
```

A1.2 DRIP

```
program flip
    character*6 hname,huse(2)
    character*8 date,user,charge,case,time
    character*8 titl(12)
    character*60 file1
C**********************************************************************
C                                                                      *
C     DELETE THE NEXT LINE.   AERS                                     *
C                                                                      *
C**********************************************************************
    file1='/scrtch/nukc/oldfort.36'                    getdo
    open(3,file=file1,status='old',form='unformatted')
    open(1,file='temp9.out',status='unknown',form='formatted')
    open(2,file='temp9.dos',status='unknown',form='formatted')
    open(4,file='fort.36',status='unknown',form='unformatted')
C**********************************************************************
C                                                                      *
C     Read FILE IDENTIFICATION                                         *
C                                                                      *
C**********************************************************************
    read(3)hname,(huse(i),i=1,2),ivers
    write(4)hname,(huse(i),i=1,2),ivers
    write(1,9020)hname,(huse(i),i=1,2),ivers
    write(*,9020)hname,(huse(i),i=1,2),ivers
 9020 format(12x,'File name ==> ',a8/2x,'User identification ==> ',a6,
   *a6/9x,'File version ==> ',i21)
C**********************************************************************
C                                                                      *
C    Read FILE LABEL                                                   *
C                                                                      *
C**********************************************************************
    read(3)date,user,charge,case,time,(titl(i),i=1,7)
    write(4)date,user,charge,case,time,(titl(i),i=1,7)
```

```
      write(1,9030)date,user,charge,case,time,(titl(i),i=1,7)
      write(2,9040)date,user,charge,case,time,(titl(i),i=1,7)
      write(*,9040)date,user,charge,case,time,(titl(i),i=1,7)
 9030 format(/8x,'Date ==> ',a8/8x,'User ==> ',a8/6x,'Charge ==> ',a8/
     *8x,'Case ==> ',a8/8x,'Time ==> ',a8//1x,'Title ==>'/2x,a6,a6,a6,
     *a6,a6,a6,a6,a6,a6,a6,a6,a6,a6,a4/)
 9040 format('!',8x,'date ==> ',a8/'!',8x,'user ==> ',a8/'!',6x,
     *'charge ==> ',a8/'!',8x,'case ==> ',a8/'!',8x,'time ==> ',a8/'!'/
     *'! title ==>'/'! ',a6,a6,a6,a6,a6,a6,a6,a6,a6,a6,a6,a4)
C*********************************************************************
C                                                                     *
C     Read FILE CONTROL                                               *
C                                                                     *
C*********************************************************************
      read(3)igm,jm,ima,mma,nintsr,njntsr,(idum,i=1,19)
      write(1,9050)igm,jm,ima,mma,nintsr,njntsr
      write(*,9060)igm,jm,ima,mma,nintsr,njntsr
      write(2,9060)igm,jm,ima,mma,nintsr,njntsr
 9050 format(21x,'No. of energy groups ==>',1x,i6/20x,
     *'Number of J intervals ==','> ',i6/20x,
     *'Number of I intervals ==','> ',i6/12x,
     *'Number of boundary direc','tions ==> ',i6/13x,
     *'Number of I-boundary sou','rces ==> ',i6/13x,
     *'Number of J-boundary sou','rces ==> ',i6)
 9060 format('!',21x,'No. of energy groups ==>',1x,i6/'!',20x,
     *'Number of J intervals ==','> ',i6/'!',20x,
     *'Number of I intervals ==','> ',i6/'!',12x,
     *'Number of boundary direc','tions ==> ',i6/'!',13x,
     *'Number of I-boundary sou','rces ==> ',i6/'!',13x,
     *'Number of J-boundary sou','rces ==> ',i6)
      CALL DAISO('readflux.inp',1,        10000)
      CALL DCOUNT('rold',nrold,1)
      CALL DCOUNT('rnew',nrnew,1)
       nrnew=nrnew-1
       nrold=nrold-1
```

```
      if(nrold.ne.100)then
        print *,' rold must have 101 values'
      CALL PFSTOP
      STOP
       endif
      write(4)igm,jm,nrnew,mma,nintsr,njntsr,(idum,i=1,19)
      call doit(igm,ism,jm,mma,ima,nrold,nrnew)
      CALL PFSTOP
      STOP
      end
C*************************************************************************
C*************************************************************************
      subroutine doit(igm,ism,jm,mma,ima,nrold,nrnew)
      parameter(nscrx=   300000)
      parameter(ncscrx=    10000)
      character*1 zca
      common/scrch/nscr,za(nscrx),izzz1,izzzm
      common/cscrch/ncscr,zca(ncscrx),izzzcm
      data ifirst/1/
      nscr0=nscr
      ncscr0=ncscr
      kz=ialc8((jm+1),'z         ')
      krold=ialc8((101),'rold      ')
      krnew=ialc8((nrnew+1),'rnew      ')
      kfluxold=ialc8((mma)*(100),'fluxold    ')
      kfluxnew=ialc8((mma)*(nrnew),'fluxnew    ')
      call zdoit
     *(igm,ism,jm,mma,ima,nrold,nrnew,
     *za(kz),za(krold),za(krnew),za(kfluxold),za(kfluxnew))
      nscr=nscr0
      ncscr=ncscr0
      return
      end
      subroutine zdoit
     *(igm,ism,jm,mma,ima,nrold,nrnew,
```

```
     *z,rold,rnew,fluxold,fluxnew)
      real z(*),rold(*),rnew(*)
      real fluxold(mma,*),fluxnew(mma,*)

      character*60 file1
      real temp(96,100)
c     do i=1,51
c       r(i)=i-1
c     enddo
c     do i=52,61
c       r(i)=r(i-1)+2.5
c     enddo
c     do i=62,81
c       r(i)=r(i-1)+1.25
c     enddo
c     do i=82,91
c       r(i)=r(i-1)+2.5
c     enddo
c     do i=92,101
c       r(i)=r(i-1)+5.0
c     enddo
     CALL DAISR('rold',0,101,rold,1)
      do 5001 i=1,101
       print *,' rold ',i,rold(i)
 5001  CONTINUE
     CALL DAISR('rnew',0,nrnew+1,rnew,1)
      do 5002 i=1,nrnew+1
       print *,' r ',i,rnew(i)
 5002  CONTINUE
C**********************************************************************
C                                                                     *
C     Read FILE INTEGER PARAMETERS                                    *
C          (Will not print because I do not use them)                 *
C                                                                     *
C**********************************************************************
```

```
      read(3)z0
      write(4)z0
      write(*,541)z0
  541 format(/7x,'Boundary source taken at',1x,'z = ',0pf8.3)
      do 5003 ig=1,igm
      read(3)((fluxold(j,i),j=1,mma),i=1,nrold)
c     write(*,'(i5,1x,f15.2,e15.8)')(i,0.5*(rold(i)+rold(i+1)),
c     *fluxold(mma,i),i=1,nrold)
c     Now mix them
      do 5004 j=1,nrold
       if(rold(j).gt.rnew(1))go to 31
 5004 CONTINUE
   31 j=j-1
      do 5005 i=1,nrnew
       do 5006 k=1,mma
        fluxnew(k,i)=0.
 5006  CONTINUE
 5005  CONTINUE
c     print *,' j = ',j
      do 5007 i=1,nrnew
c      print *,' For i = ',i
      rmin=rnew(i)
   33  rmax=rold(j+1)
c     print *,' Is rnew(i+1) > rmax ',rnew(i+1),rmax
      if(rnew(i+1).lt.rmax)rmax=rnew(i+1)
      frac=(rmax-rmin)/(rnew(i+1)-rnew(i))
c     print *,' frac is now ',frac
      do 5008 k=1,mma
       fluxnew(k,i)=fluxnew(k,i)+frac*fluxold(k,j)
 5008  CONTINUE
c      print *,' old flux is now ',fluxold(mma,j)
c      print *,' new flux is now ',fluxnew(mma,i)
      if(rmax.eq.rnew(i+1))then
c       print *,' Go on to next i'
       go to 32
```

```
      endif
      j=j+1
      if(j.gt.nrold)go to 41
c      print *,' Go to next j'
        rmin=rmax
      go to 33
   32 CONTINUE
 5007 CONTINUE

   41  continue
     write(*,'(i5,1x,f15.2,e15.8)')(i,0.5*(rnew(i)+rnew(i+1)),
     *fluxnew(mma,i),i=1,nrnew)
     write(4)((fluxnew(j,i),j=1,mma),i=1,nrnew)
 5003 CONTINUE
     zero=0.
c    This writes the gamma groups as zeroes
     do 5009 ig=1,84-igm
     write(4)((zero,j=1,mma),i=1,nrnew)
 5009 CONTINUE
     write(4)fluxnew(1,1)
     close(4)
     return
     end
C*********************************************************************
C*********************************************************************
     subroutine rdflux(igm,jm,imbisx,imbis,iset,mma,isbt,neut,r,z,
     *                 ndes)
     parameter(nscrx=   300000)
     parameter(ncscrx=    10000)
     character*1 zca
     common/scrch/nscr,za(nscrx),izzz1,izzzm
     common/cscrch/ncscr,zca(ncscrx),izzzcm
     data ifirst/1/
     nscr0=nscr
     ncscr0=ncscr
```

```
kflum=ialc8((imbisx)*(jm)*(igm),'flum      ')
kdose=ialc8((imbisx)*(jm)*(3),'dose      ')
kdneut=ialc8((igm),'dneut      ')
kfdose=ialc8((igm),'fdose      ')
kden=ialc8((imbisx)*(jm),'den      ')
kzdes=ialc8((ndes),'zdes      ')
krdes=ialc8((ndes),'rdes      ')
kpoints=ialc8((ndes*2),'points      ')
kides=ialc8((ndes),'ides      ')
kjdes=ialc8((ndes),'jdes      ')
call zrdflux
*(igm,jm,imbisx,imbis,iset,mma,isbt,neut,r,z,
*              ndes,
*za(kflum),za(kdose),za(kdneut),za(kfdose),za(kden),za(kzdes),
*za(krdes),za(kpoints),za(kides),za(kjdes))
nscr=nscr0
ncscr=ncscr0
return
end
subroutine zrdflux
*(igm,jm,imbisx,imbis,iset,mma,isbt,neut,r,z,
*              ndes,
*flum,dose,dneut,fdose,den,zdes,rdes,points,ides,jdes)
real flum(imbisx,jm,*),dose(imbisx,jm,*)
real dneut(*),fdose(*),den(imbisx,*)
real zdes(*),rdes(*),points(*)
integer ides(*),jdes(*)

character*32 drf
character*60 file1
character*80 file,title
real r(*),z(*),r0(2),z0(2)
integer imbis(*),iset(*)
CALL DAISR('points',0,ndes*2,points,1)
do 5010 i=1,ndes
```

```
      rdes(i)=points(2*i-1)
      zdes(i)=points(2*i)
 5010 CONTINUE
     do 5011 i=1,igm
      dneut(i)=1.
 5011 CONTINUE
C*************************************************************************
C                                                                        *
C    THE NEXT FACTOR IS A HARDWIRED SCALING FACTOR                       *
C                                                                        *
C*************************************************************************
     fact=(91.3*91.3)/(53.66*53.66)
C*************************************************************************
     write(*,9010)
 9010 format(/3x,'What is the file name fo','r the dose response func',
    *'tions?'/)
     read(*,'(a60)')file1
     if(file1.ne.'')then
     CALL DCLEAR
     CALL DAISO(file1,1,        10000)
     CALL DAISR('drf',0,igm,dneut,1)
     else
      print*,' What group do you want?'
      read(*,'(bn,i10)')igdes
      do 5012 i=1,igm
       dneut(i)=0
 5012  CONTINUE
      dneut(igdes)=1.
     endif
     do 5013 i=1,imbisx
      do 5014 j=1,jm
       dose(i,j,1)=0.
       dose(i,j,2)=0.
 5014  CONTINUE
 5013 CONTINUE
```

```
C*********************************************************************
C                                                                     *
C   Read SCALAR FLUX MOMENTS                                          *
C                                                                     *
C*********************************************************************
    imb=imbis(isbt)
C*********************************************************************
C*********************************************************************
    do 5015 ig=1,igm
     print*,' Group ',ig
     do 5016 j=1,jm
      is=iset(j)
      ims=imbis(is)
      read(3)(flum(i,j,ig),i=1,ims)
      do 5017 i=1,ims
       flum(i,j,ig)=flum(i,j,ig)*fact
5017    CONTINUE
      do 5018 i=1,ims
       if(ig.le.neut)then
        dose(i,j,1)=dose(i,j,1)+flum(i,j,ig)*dneut(ig)
       else
        dose(i,j,2)=dose(i,j,2)+flum(i,j,ig)*dneut(ig)
       endif
5018    CONTINUE
C*********************************************************************
C                                                                     *
C       write(1,9030)(ig,j,i,flum(i,j),i=1,ims)                       *
C                                                                     *
C*********************************************************************
9020 format(2x,i3,2x,i3,1x,i3,2x,2pe15.8)
5016  CONTINUE
     read(3)
5015 CONTINUE
    write(2,9030)(imbis(iset(j)),j=1,jm)
9030 format('!'/'!',3x,'Scalar dose in format'/'!'/'!',6x,
```

```
     *'((dose(i,j),i=1,imbis(j)',')',j=1,jm)'/'!'/'!',6x,
     *'where the IMBIS are the ','number of I nodes'/'!',8x,
     *'per J level'/'!'/'!',4x,'Here are the IMBIS value','s -'/'!'/5x,
     *'imbis ='/(1x,i4,1x,i4,1x,i4,1x,i4,1x,i4,1x,i4,1x,i4,1x,i4,1x,i4,1x,i4,
     *1x,i4,1x))
      write(2,9040)
 9040 format('!'/'!',3x,'Neutron scalar doses -'/'!'/2x,'n_dose =')
      do 5019 j=1,jm
       zmid=0.5*(z(j)+z(j+1))
       write(2,9050)zmid,(dose(i,j,1),i=1,imbis(iset(j)))
 5019 CONTINUE
 9050 format('!',2x,'Height = ',0pf12.5/(1x,2pe11.4,1x,2pe11.4,1x,
     *2pe11.4,1x,2pe11.4,1x,2pe11.4))
      write(2,9060)
 9060 format('!'/'!',3x,'Gamma scalar doses -'/'!'/2x,'g_dose =')
      do 5020 j=1,jm
       zmid=0.5*(z(j)+z(j+1))
       write(2,9050)zmid,(dose(i,j,2),i=1,imbis(iset(j)))
 5020 CONTINUE
C*********************************************************************
C                                                                    *
C    Combine neutron and gamma into a total dose                     *
C                                                                    *
C*********************************************************************
      do 5021 j=1,jm
       do 5022 i=1,imbis(iset(j))
        dose(i,j,3)=dose(i,j,1)+dose(i,j,2)
 5022   CONTINUE
 5021 CONTINUE
C*********************************************************************
C                                                                    *
C    For each of the desired points                                  *
C                                                                    *
C*********************************************************************
      nz=jm
```

```
      nr=imbisx
      do 5023 id=1,ndes
       write(*,9070)id,rdes(id),zdes(id)
 9070 format(/'========================','========================',
     *'==============='//3x,'Desired point #',i4,2x,'(',0pf9.4,',',
     *0pf9.4,')'/)
C*************************************************************************
C                                                                        *
C     Find the (i,j) point                                               *
C                                                                        *
C*************************************************************************
       if(rdes(id).lt.r(1).or.rdes(id).gt.r(nr+1))then
        write(*,9080)rdes(id),r(1),r(nr+1)
 9080 format(/2x,'Listen, you dummy!',3x,'The desired R point, ',
     *0pf9.5/4x,'is outside the data rang','e ==> (',0pf9.5,', ',
     *0pf7.3,')'//5x,'Ignoring that point...'/)
        go to 30
       endif
       if(zdes(id).lt.z(1).or.zdes(id).gt.z(nz+1))then
        write(*,9090)zdes(id),z(1),z(nz+1)
 9090 format(/2x,'Listen, you dummy!',3x,'The desired Z point, ',
     *0pf9.5/4x,'is outside the data rang','e ==> (',0pf9.5,', ',
     *0pf7.3,')'//5x,'Ignoring that point...'/)
        go to 30
       endif
       do 5024 ir=1,nr
        if(rdes(id).lt.r(ir+1))go to 10
 5024  CONTINUE
  10   i=ir
       do 5025 iz=1,nz
        if(zdes(id).lt.z(iz+1))go to 20
 5025  CONTINUE
  20   j=iz
       write(*,9100)i,j
 9100 format(/9x,'The point is in cell (',i4,',',i4,')'/)
```

```
C*********************************************************************
C                                                                     *
C     Print the table                                                 *
C                                                                     *
C*********************************************************************
      tdos=0.
      do 5026 ig=1,igm
       fdose(ig)=flum(i,j,ig)*dncut(ig)
       tdos=tdos+fdose(ig)
 5026  CONTINUE
      write(*,9110)
      do 5027 ig=1,igm
       perc=fdose(ig)/tdos*100.
       if(perc.gt.0.)write(*,9120)ig,flum(i,j,ig),fdose(ig),perc
 9110 format(/9x,'Group',5x,'Flux',10x,'Dose',9x,'%'/9x,
     *'===== ============= ====','========== ======')
 9120 format(9x,i4,2x,1pe13.6,1x,1pe14.7,1x,0pf6.2)
 5027  CONTINUE
  30 CONTINUE
 5023 CONTINUE
C*********************************************************************
C                                                                     *
C    Make the dose map                                                *
C                                                                     *
C*********************************************************************
     print*,' What do you want the .PS dos','e file to be?'
     read(*,'(a30)')file
     title='Dose map for file '//file(1:30)
     nx0=1
     ny0=1
     r0(1)=r(1)
     r0(2)=r(nr+1)
     z0(1)=z(1)
     z0(2)=z(nz+1)
     do 5028 i=1,nr
```

```
      do 5029 j=1,nz
        den(i,j)=alog(dose(i,j,3))
 5029   CONTINUE
 5028 CONTINUE
      call makeps(r0,z0,nx0,ny0,den,r,z,nr,nz,title,file,1)
      return
      end
C*********************************************************************
C*********************************************************************
      subroutine makeps(x0,y0,nx0,ny0,den,x,y,nx,ny,title,file,inorm)
c*********************************************************************#
C
C Module name:
C   MAKEPS
C
C Called modules:
C   DRBEGIN DRTHICK DRTYPE DRFBOX DRBOX DREND LENG
C
C Called by:
C   DETERM  DOIT
C
C External variables - used:
C   DEN (nx,ny)            R*4
C   FILE                C*80
C   INORM                  I*4
C   NX                  I*4
C   NX0                 I*4
C   NY                  I*4
C   NY0                 I*4
C
C*********************************************************************
      parameter(nscrx=   300000)
      parameter(ncscrx=    10000)
      character*1 zca
      common/scrch/nscr,za(nscrx),izzz1,izzzm
```

```
      common/cscrch/ncscr,zca(ncscrx),izzzcm
      data ifirst/1/
      nscr0=nscr
      ncscr0=ncscr
      kcolor=ialc8((nx)*(ny),'color      ')
      call zmakeps
     *(x0,y0,nx0,ny0,den,x,y,nx,ny,title,file,inorm,
     *za(kcolor))
      nscr=nscr0
      ncscr=ncscr0
      return
      end
      subroutine zmakeps
     *(x0,y0,nx0,ny0,den,x,y,nx,ny,title,file,inorm,
     *color)
      real color(nx,*)

      real x0(nx0+1),y0(ny0+1)
      real x(nx+1),y(ny+1),den(nx,ny)
      character*80 title,file,aline
C*************************************************************************
C                                                                        *
C    Sort the material densities                                         *
C                                                                        *
C*************************************************************************
      wtmax=-1000000000.
      do 5030 j=1,ny
       do 5031 i=1,nx
        if(den(i,j).gt.wtmax)wtmax=den(i,j)
 5031   CONTINUE
 5030 CONTINUE
      if(inorm.eq.0)then
       wtmin=0.
      else
       wtmin=1000000000.
```

```
      do 5032 j=1,ny
       do 5033 i=1,nx
        if(den(i,j).lt.wtmin)wtmin=den(i,j)
5033    CONTINUE
5032  CONTINUE
    endif
    if(wtmax.le.wtmin)wtmax=wtmin+1.
    do 5034 j=1,ny
     do 5035 i=1,nx
      frac=(den(i,j)-wtmin)/(wtmax-wtmin)
      color(i,j)=1.-frac
5035  CONTINUE
5034 CONTINUE
C*************************************************************************
C                                                                        *
C   Initialize the DRAW subroutines                                      *
C                                                                        *
C*************************************************************************
    call drbegin(x0(1),y0(1),x0(nx0+1),y0(ny0+1),title,file)
C*************************************************************************
C                                                                        *
C   Draw the calculational cells                                         *
C                                                                        *
C*************************************************************************
    call drthick(.001)
    call drtype('dashed')
    do 5036 j=1,ny
     do 5037 i=1,nx
      call drfbox(x(i),y(j),x(i+1),y(j+1),color(i,j))
5037  CONTINUE
5036 CONTINUE
    call drtype('solid')
C*************************************************************************
C                                                                        *
C   Draw the bounding box                                                *
```

```
C                                                                       *
C***********************************************************************
      call drbox(x0(1),y0(1),x0(nx0+1),y0(ny0+1))
C***********************************************************************
C                                                                       *
C     Draw the boxes of original mesh                                   *
C                                                                       *
C***********************************************************************
      density=1.
      do 5038 i=1,nx0
       do 5039 j=1,ny0
        jj=ny0+1-j
        call drbox(x0(i),y0(j),x0(i+1),y0(j+1))
 5039   CONTINUE
 5038 CONTINUE
C***********************************************************************
C                                                                       *
C     End the DRAW subroutine set                                       *
C                                                                       *
C***********************************************************************
      call drend
      aline='xpsview '//file(1:leng(file,32))//' &'
      call system(aline)
      return
      end
      function ialc8(nn,avar)
      character*12 avar
      parameter(nscrx=    300000)
      parameter(ncscrx=     10000)
      character*1 zca
      common/scrch/nscr,za(nscrx),izzz1,izzzm
      common/cscrch/ncscr,zca(ncscrx),izzzcm
      if(nscr.eq.0)then
       nscr=1
       izzz1=1
```

```
      izzzm=1
     endif
     ialc8=nscr
     nscr=nscr+nn
     if(nscr.gt.nscrx)then
     write(*,9999)avar,nn,nscr
9999  format(31h No more REAL/INT scratch room.,
    *7h   Var ,a,6h Leng ,i9,13h Requested = ,i9)
     stop
     endif
     if(nscr.gt.izzzm)izzzm=nscr
     return
     end
     function icalc8(nn)
     parameter(nscrx=   300000)
     parameter(ncscrx=    10000)
     character*1 zca
     common/scrch/nscr,za(nscrx),izzz1,izzzm
     common/cscrch/ncscr,zca(ncscrx),izzzcm
     if(ncscr.eq.0)then
      ncscr=1
      izzzcm=1
     endif
     icalc8=ncscr
     ncscr=ncscr+nn
     if(ncscr.gt.ncscrx)then
     write(*,9999)
9999  format(50h  There is not enough CHAR scratch room. Stopping.)
     stop
     endif
     if(ncscr.gt.izzzcm)izzzcm=ncscr
     return
     end
     subroutine pfstop
     parameter(nscrx=   300000)
```

```
      parameter(ncscrx=     10000)
      character*1 zca
      common/scrch/nscr,za(nscrx),izzz1,izzzm
      common/cscrch/ncscr,zca(ncscrx),izzzcm
      ratio1=(izzzm*1.)/(nscrx*1.)*100.
      ratio2=(izzzcm*1.)/(ncscrx*1.)*100.
      write(*,9999)izzzm,nscrx,ratio1
 9999  format(/17h TEMP9      used ,i10,8h out of ,i10,
     *25h real/integer variables (,f8.3,2h%))
      write(*,9998)izzzcm,ncscrx,ratio2
 9998  format(12x,5h and ,i10,8h out of ,i10,
     *12h characters ,12x,1h(,f8.3,2h%)/)
      return
                                                    end
```

Appendix 2

Economics

Table 1. Facility Expenses [40]

Clinical Operations	1996 dollars
Labor	4406160
Benefits and Taxes	1365910
Clinic Overhead	410879
Medical Supplies	88647
Medical Equipment Maintenance	26594
Total Clinical Operations	6298190
Clinical Overhead	
Facilities maintainance	35459
Telephone	8865
Utilities	19946
Insurance	88647
Office Supplies	8865
Travel	2659
Meetings and Conferences	3546
Postage and Delivery	3546
Legal and Professional	88647
Consultants	53188
Licenses and Fees	53188
Information Systems Maintenance	17729
Employee Development	26594
Total Clinical Overhead	410879
Reactor Operations	
S/C Nuclear Engineering Operations	100000
Nuclear Supplies	93080
Reactor Maintenance	37232
Reactor Overhead	1195291
Total Reactor Operations	1425603

Reactor Overhead	
Facilities Maintenance	17729
Facilities Rent	1099996
Telephone	8865
Utilities	8865
Insurance	35459
Office Supplies	3546
Travel	2659
Meeting and Conferences	1330
Postage and Delivery	2659
Legal and Professional	4432
Consultants	0
Licenses and Fees	3546
Information Systems Maintenance	4432
Employee Development	1773
Total Reactor Overhead	1195291
Expenses	
Clinical Operations	6298190
Clinical Overhead	410879
Reactor Operations	1425603
Reactor Overhead	1195291
Research	4700000
Total Expenses	$14029963
Personnel	
Executive Director	203612
Dep. Executive Director	179178
Administrative Director	179178
Personnel Manager	105878
Patient Services Manager	105878
Staff (Emp-1)	40722
Staff (Emp-2)	40722
Accounting	105878
Maintenance (Facility)	52125
Staff (Emp-1)	28506
Staff (Emp-2)	28506
Housekeeping	57011
Staff (Emp-1)	36650
Staff (Emp-2)	36650

Maintenance (Grounds)	52125
Staff (Emp-1)	28506
Staff (Emp-2)	28506
Patient QA Director	105878
Director of Research	203612
Compound Development	81445
Diagnostic Systems	81445
Nuclear Systems	81445
Medical Sys. and Prac.	81445
Director of Reactor Operations	179178
Nuclear QA Manager	105878
Reactor Operator (1)	81445
Reactor Operator (2)	81445
Reactor Operator (3)	81445
Staff (1)	52125
Staff (2)	52125
Director of Therapy	203612
Chief of Nursing	154745
Nursing Staff	195467
Therapy Scheduler	52125
Chief of Services	0
Neurosurgery	407224
Thoracic Surgery	407224
Radiology	407224
Total Personnel Costs	4406163
Primary Brain Tumors	
Telemedicine Software	1800
Linkage	1200
Prequalification	
MRI (regular)	18000
MRI (boron)	42000
PET (boron)	48000
Neurosurgery	
Operating Theater	300000
Recovery	60000
Hospital (other-2 days)	60000
Compound (Pharmacy)	
MRI/PET	30000
Therapy	30000
BNCT	179892
Total Primary Brain Tumor Cost	770892

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